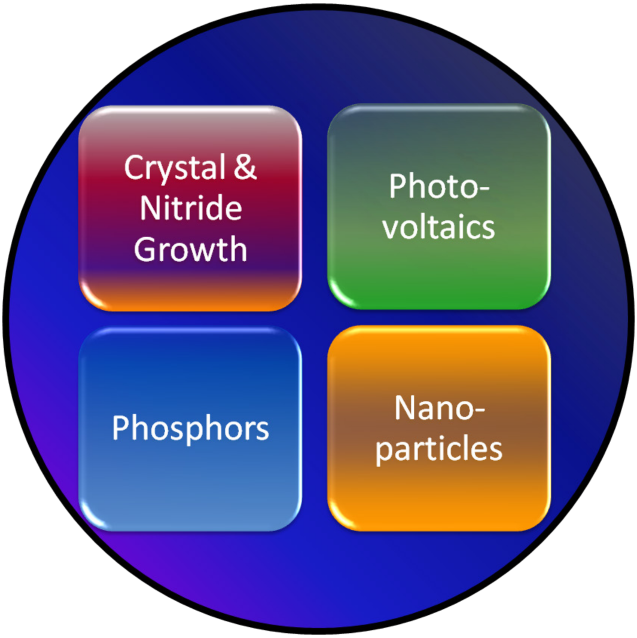
FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG
TECHNISCHE FAKULTÄT

Department of Materials Science and Engineering

i-MEET

Materials for Electronics and Energy Technology



ANNUAL REPORT 2017

Prof. Dr. Christoph J. Brabec
Prof. Dr.-Ing. Peter Wellmann
Prof. Dr. Wolfgang Heiß
PD Dr. Miroslaw Batentschuk
Prof. Dr. rer. nat. Albrecht Winnacker

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1. Vorwort/Preface

Herzlichen Dank an unsere Studenten, Doktoranden, Mitarbeiter und Gruppenleiter für ihr überdurchschnittliches Engagement und ihre herausragenden Leistungen in 2017. Mit über 100 Manuskripten, unter anderem in Zeitschriften wie Nature, Science und Energy & Environmental Science, hat das i-MEET wesentlich dazu beigetragen, dass die FAU im jüngsten Singapur Universitäts-Ranking im Thema Energy Technology (Energy Engineering) einen Spitzenplatz (Platz 21) belegt.
Besonders herzlichen Dank an unser Verwaltungsteam und unsere technischen Angestellten – ohne sie wäre es nicht möglich, das i-MEET so erfolgreich zu führen.

Ihnen allen, den Kooperationspartnern und Unterstützern des i-MEET danke ich für die erfolgreiche Zusammenarbeit in 2017 und wünsche viel Spaß beim Lesen unseres Tätigkeitsberichts.

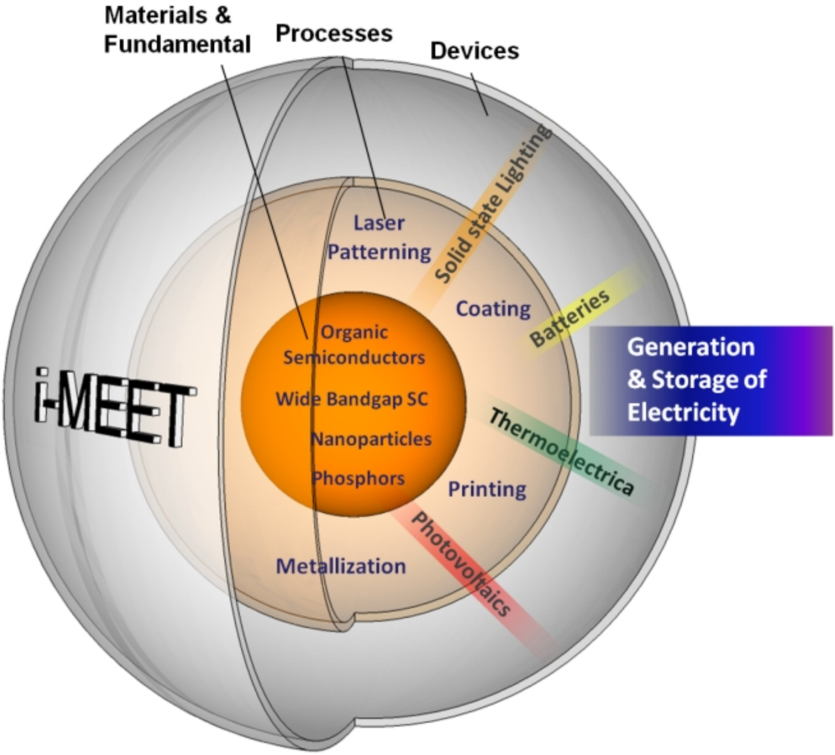
At this stage I want to express my gratitude to our students, PhD students, postdocs and group leaders for their fantastic scientific achievements in 2017. We published over 100 manuscripts, many of them in highly ranked journals like Nature, Science or Energy & Environmental Science which made a major contribution to the success that FAU was ranked for the first time at a top position in the Singapore University Ranking (rank 21 in Energy Engineering).
Specific and particular thanks to our technical and admin staff for their outstanding commitment and support. i-MEET would not be that successful without their dedication.

Finally, let me thank you, our cooperation partners and supporters of i-MEET, for a successful cooperation in 2017! I wish you an enjoyable time reading our annual report.

Best, Christoph Brabec

Please note that some of our highlights can be found on i-MEET's youtube channel i-MEET Lab.
(https://www.youtube.com/channel/UC6RHRl5xyzL1b-lcJ6FG3PA).

Please note also our alumni network at LinkedIn (Institute i-MEET).



(Christoph J. Brabec)

P. Well

(Peter Wellmann)

Wolfgang Heiß

(Wolfgang Heiß)

A. Winnacker

(Albrecht Winnacker)

M. Batentschuk

(Miroslaw Batentschuk)

Erlangen, May 2018

2. Members of the Chair

Professors

Prof. Dr.
Christoph J. Brabec
Head of the chair

Prof. Dr.-Ing.
Peter Wellmann

Prof. Dr.
Wolfgang Heiß

Secretaries

Manuela Baumer

Elisabeth Henneberger

Ulrike Knerr

Claudia Koch

Sandra Wehlmann

Academic administration

PD Dr. Miroslaw Batentschuk

Professors emeritus

Prof. Dr. rer. nat.
Georg Müller

Prof. Dr. rer. nat.
Albrecht Winnacker

Associate Professors

Prof. Dr. Dr.-Ing. habil.
Michael Thoms

Assistant lecturer

Dr.rer.nat.
Christian Camus

Dr.
Hans-Joachim Egelhaaf

Dr.-Ing.
Ulrike Künecke

Technical staff

Elena Epelbaum

Tina Foth

Silvan Heilscher

Felix Holler

Leonid Kuper

Edeltraud Völkel

Helena Waldau

Corina Winkler

Ronald Wirth

Solar and Semiconductor Devices (SSD)

(Scientifical staff, doctoral candidates)

Prof. Dr.
Christoph J. Brabec
Group leader

Research of the device group is devoted to the design, simulation, processing and analysis of modern innovative semiconductors, electronic materials as well as advanced devices. Next generation concepts for electronic devices and future light harvesting techniques complete our research focus.

Development of low cost, long lived and highly efficient printed solar cells is one major vision of this research group. This includes the development of stable and efficient materials, the development of printed multilayer tandem technologies, ternary sensitization and controlling microstructure formation. Advanced organic semiconductors, p-type & n-type interface layers, printed transparent / opaque electrodes, flexible substrates and low cost barriers are further activities of this research group.

Organic semiconductors, perovskite hybrid composite semiconductors as well as colloidal quantum dots are the material fundament of our device engineering and process development activities. Further activities include low temperature processed chalcogenides and kesterites.

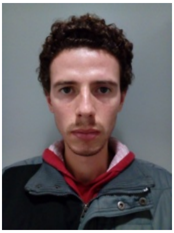
Dipl.-Phys.
Klaus Burlafinger
Doctoral candidate
i-MEET

Haiwei Chen
MSc
Doctoral candidate
i-MEET

Shi Chen
MEng
Doctoral candidate
i-MEET

Jack Elia
MSc
Doctoral candidate
i-MEET

Shuai Gao
MSc
Doctoral candidate
i-MEET



José Garcia Cerrillo
MEng
Doctoral candidate
i-MEET

Ening Gu
MEng
Doctoral candidate
i-MEET

Yakun He
MEng
Doctoral candidate
i-MEET

Dr.-Ing.
Thomas Heumüller
Postdoc
i-MEET

Yi Hou
MEng
Doctoral candidate
i-MEET

Simon Kahmann
MSc
Doctoral candidate
i-MEET

Andre Karl
MSc
Doctoral candidate
i-MEET

Laraib Khanzada
MEng
Doctoral candidate
i-MEET

Stefan Langner
MSc
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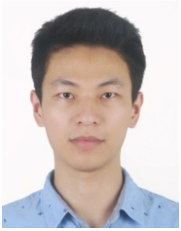
i-MEET

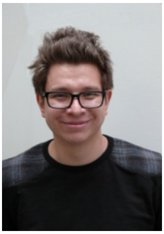
Dr.
Ning Li
Postdoc
i-MEET

Chao Liu
MSc
Doctoral candidate
i-MEET



Wei Meng
MSc
Doctoral candidate
i-MEET

J. D. Perea Ospina
MSc
Doctoral candidate
i-MEET



C.O. Ramirez Quiroz
MSc
Doctoral candidate
i-MEET

Dr.
Michael Salvador
Postdoc
i-MEET

MSc
George Spyropoulos
Doctoral candidate
i-MEET

Chen Xie
MSc
Doctoral candidate
i-MEET

Junyi Xu
MEng
Doctoral candidate
i-MEET

Chaohong Zhang
MSc
Doctoral candidate
i-MEET

Transport in Solution-Processed Semiconductors (TSC)

(Scientifical staff, doctoral candidates)

Dr. Dipl.-Ing. Gebhard Matt
Group leader

Our research focus is in the electro-optical characterization of solution processed semiconductors.

We are specially interested in the nature of the charge transport in these exciting material systems. Sensitive methods have been developed for the detection of photo-currents in steady-state as well as time-resolved (ns regime) covering a wide spectral range from the UV-VIS to the Mid-IR.

Especially we are able to measure important material parameters as the charge carrier mobility and life-time by different methods as Time-of-Flight, charge extraction (CELIV) and transient photo-voltage (TPV).

Are more recent research focus is on the detection of high energetic radiation (X-ray, gamma-ray).

Osbel Almora Rodríguez
MSc
Doctoral candidate
iMEET

Classen Andrej
MSc
Doctoral candidate
i-MEET

Simon Kahmann
MSc
Doctoral candidate
i-MEET

Shreetu Shrestha
MSc
Doctoral candidate
i-MEET

Xiaofeng Tang
MSc
Doctoral candidate
i-MEET

Phosphors & Light (P&L)

(Scientifical staff, doctoral candidates)

Dr. rer. nat. (Postdoc)
Karen Forberich
Group leader **Light management**

The main aim of the 'light management' group is to improve the optical properties of printed electronic devices, particularly the light harvesting in printed solar cells.

The experimental activities include light conversion, i.e. the transformation of UV and infrared light into visible light that can be converted by the solar cell, solution-processed electrodes, solution-processed dielectric mirrors, and the experimental investigation of light propagation in particle-matrix systems.

Optical simulations are another important part of the activities. We are using several different methods like FIT-THIIM, Ray-Tracing, RCWA and the transfer matrix formalism, and we combine different methods, but also different techniques for optical modelling. Optical models are verified by experimental measurements before they are used for numerical optimization.
For each problem, we will choose the most suitable method, i.e. the one that delivers the most accurate results at a reasonable computational effort.

Carina Bronnbauer
MSc
Doctoral candidate
i-MEET

Shuai Gao
MSc
Doctoral candidate
i-MEET

Kerstin Krebs
MSc
Doctoral candidate
i-MEET

Ternary Sensitization (TS)

(Scientifical staff, doctoral candidates)

Dr.
Tayebeh Ameri
Group leader

This research group aims to overcome the photocurrent and the performance limitation of polymer:fullerene solar cells in a simple single-junction structure by introducing a sensitizer with complementary absorption profile into the host matrix. To boost near infrared light harvesting, we examine different semiconductor systems such as low bandgap polymers, small molecules, dye compounds as well as hybrid and inorganic nanoparticles / nanostructures. We carry out in-depth investigations on how the structural properties of the host system as well as the sensitizer will be influencing microstructure formation and the functionality of ternary systems. To illuminate on the modified recombination mechanisms in ternary systems, we also investigate the charge or energy transfer and charge transport between the constituent components. We employ various advanced microscopic, spectroscopic and optoelectronic techniques to study the morphology and transport of ternary hybrid and organic solar cells. Furthermore, we aim to use empirical and simulation techniques to learn about the origin of Voc in ternary solar cell. Investigation of the lifespan of the ternary devices compared to their host references is also one important part of our research.

Nicola Gasparini
MSc
Doctoral candidate
i-MEET

Lili Ke
MSc
Doctoral candidate
i-MEET

Ali Ashtiani
MSc
Doctoral candidate
i-MEET

Phosphors & Light (P&L)

(Scientifical staff, doctoral candidates)

PD Dr.
Miroslaw Batentschuk
Group leader **Phosphors**

Dr. (Postdoc)
Andres Osvet
Group leader **Phosphors**

The research of the „Phosphors" group is concentrated on the development of new phosphors, first of all for the light harvesting in solar cells, based on up and down conversion of the solar emission. In addition, new light-converting luminescent materials for white light emitting diodes, as well as storage phosphors for the application as markers in the medical and biological research are developed and studied. New phosphors for the high temperature thermometry are another part of activities, in co-operation with EnCN. Our expertize in optical spectroscopy is used in close cooperation with the Organic and Solution-based Photovaltaics Groups in the development and optical characterization of solar cell materials.

Amjad Ali
MSc
Doctoral candidate
i-MEET

Liudmyla Chepyga
MSc
Doctoral candidate
i-MEET

Dipl.-Chem.
Ievgen Levchuk
Doctoral candidate
i-MEET

Solution-Processed-Semiconductor-Materials (SOPSEM)

(Scientifical staff, doctoral candidates)

Prof. Dr.
Wolfgang Heiß
Group leader

Solution processed semiconductor materials are synthesized as a basis for the development of electronic devices. The materials include colloidal nanocrystal quantum dots, organic pigment materials, and metal-halide perovskites. Recent achieved milestones include the use of organic pigments as electrophotocatalysts for the environmental friendly generation of hydrogen peroxide, and the clarification of galvanic exchange reactions in metal nanoparticles protected by metal-oxide shells. Largely improved infrared detecting materials have been obtained by merging the advantages of PbS nanocrystals with that of metal-halide perovskites semiconductors. As a novel type of ligands for nanocrystals, zero-dimensional perovskite clusters have been introduced by us, enabling the formation of an epitaxial ligand shell during a simple ligand exchange procedure. The epitaxial shell is proven to provide several advantages in optoelectronic devices, due to the good surface passivation, the formation of a semiconducting matrix, and the appealing electronic properties of the nanohybrid materials.

Niall Killilea
MSc
Doctoral candidate
i-MEET

Oleksandr Mashkov
MSc
Doctoral candidate
i-MEET

Dr.
Mykhailo Sytnyk
Postdoc
i-MEET

YousefiAmin Amir
MSc
Doctoral candidate
i-MEET

Crystal Growth Lab (CGL)

(Scientifical staff, doctoral candidates)

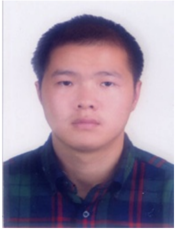
Prof. Dr.-Ing. Peter Wellmann
Group leader

The research activities in the crystal growth lab of Prof. Dr.-Ing. Peter Wellmann at the electronic materials and energy technology (i-meet) division of the materials department (University of Erlangen-Nürnberg) are devoted to modern topics in semiconductor technology and include crystal growth, epitaxy and characterization of various electronic materials. In the current focus of research and development are materials for energy saving: (i) Silicon carbide for power electronic devices is a key player for energy saving. (ii) The CIGSSe thin film solar cell materials recently have reached a maturity that allows the realization of commercial solar panels. CZTSSe is believed to play the role of a succeeding thin film solar cell material. (iii) Printed electronic layers offer a great potential of a wide range of (opto-)electronic and photovoltaic device applications. (iv) In the field of characterization a large variety of electrical, spectroscopic and structural techniques are used which serve the better understanding of materials processing. Special emphasis is put on topographic methods. (v) In all fields service for industrial and institutional partners may be provided.

Soraya Abdelhaleem
MSc
Doctoral candidate
i-MEET

Matthias Arzig
MSc
Doctoral candidate
i-MEET

Dipl.-Ing.
Lars Fahlbusch
Doctoral candidate
i-MEET



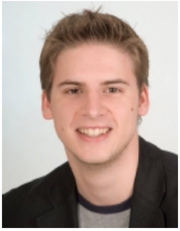
Yao Gao
MSc
Doctoral candidate
i-MEET

Ayat Hassanien
MSc
Doctoral candidate
i-MEET

Dr. Dipl.-Ing
Ulrike Künecke
Scientifical staff
i-MEET

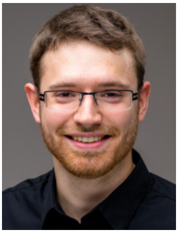
Saskia Schimmel
MSc
Doctoral candidate
i-MEET

Michael Schöler
MSc
Doctoral candidate
i-MEET



Philipp Schuh
MSc
Doctoral candidate
i-MEET

Matthias Schuster
MSc
Doctoral candidate
i-MEET



Johannes Steiner
MSc
Doctoral candidate
i-MEET

Dipl.-Ing.
Martin Wilhelm
Doctoral candidate
i-MEET

Bavarian Center for Applied Energy Research

(ZAE, doctoral candidates, postdocs)

The Bavarian Center for Applied Energy Research (ZAE Bayern) is a registered, non-profit association. The association was founded in December 1991 to promote energy research as well as education, further training, consultation, information and documentation in all fields significant to energy research. The association supports a scientific research institute with divisions in Würzburg, Garching, Erlangen, Nuremberg and Hof, employing more than 200 scientists, technicians, administrative personnel and students. Since the founding of ZAE Bayern in 1991, ZAE has become a both nationally and internationally recognized research institute.

ZAE Bayern works on the interface between evidence-based fundamental and applied industrial research. Every year the institute performs a great number of projects with the industry, from SME to large groups, as well as with university and non-university research partners. The core competences of the ZAE location in Erlangen with its subsidies in Nürnberg and Hof/Arzberg are renewable energies, with a strong focus on photovoltaics. Competences in materials science, theoretical understanding, and fundamental developments are linked in a knowledge- based chain of value with i-MEET. The close cooperation between i-MEET as well as further partners from FAU allows the ZAE Bayern in Erlangen to concentrate on finding effective solutions to remove the barriers on our way towards a green, sustainable and renewable future.

Christian Berger
MSc

Josef Bogenrieder
MSc

Iftikhar Channa
MEng

Manuel Dalsass
Dipl.-Wirt.Ing

Bernd Doll
MSc

Dipl.-Phys.
Frank Fecher

Sarmad Feroze
MSc

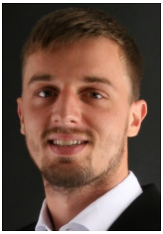
Johannes Hepp
MSc

Philipp Maisch
MSc

Dipl.-Phys.
Markus Pröll

Dipl.-Phys.
Arne Riecke

G. Spyropoulos
MSc



Christoph Stegner
MSc

Kai Cheong Tam
MPhil

Dipl.-Ing.
Stephan Wittmann

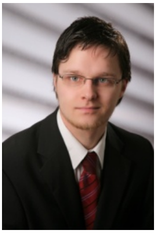
External doctoral candidates

Hermann Bechert
MSc
Osram

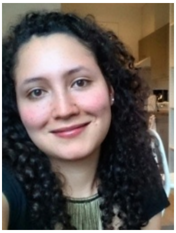
Fabian Carigiet
MSc
ZHAW

Rene Fischer
Siemens

A. Heinrichsdobler
MSc
Osram



MEng
Tobias Kötter
Siemens



Montenegro Benavides
Cindy Alexandra
Siemens

Dipl.-Ing.
Tobias Sauermann
Belectric

Dipl.-Ing
Philipp Schwamb
Osram

Visitors

26. – 30.06.2017
Prof. Dr. hab. Yuriy Zorenko (Institute of Physics Kazimierz Wielki Univerity Bydgoszcz, Poland)

26. – 30.06.2017
Prof. Van Deun (Uni-Gent, Belgien)

01.09.2017 – 12.02.2018
Baobing Fan

Maryam Alimoradi Jazi (Utrecht University, NL)

Shun Manabe (Nagoya Institute of Technology, Japan)

Maciej Gryszel (Linköping University, Sweden)

3. Bachelor Theses

Barthel, Vincent (Wellmann)
Herstellung und Charakterisierung eines CISe-Solarzellenabsorbers mit Cu-In, Se und Cu_2*-xSe Nanopartikeln*

Böse, Tillman (Brabec)
Automatisierung von Strom-Spannungsmessungen an organischen Solarzellen

Buchta, Eva (Brabec)
Comparative long-term evaluation of different PV-technologies

Fraune, Leon (Brabec)
Fabricating solution-processed organic solar cells on large substrates with a spincoater

Heinlein, Lukas (Wellmann)
Einfluss der Baffle-Geometrie auf die Auftriebskonvektion im ammonothermalen Autoklaven - Untersuchung mittels Temperaturmessung im Fluid

Ihle, Jonas (Wellmann)
Untersuchung der ammonothermalen Kristallisation von GaN mittels Aufprägung lokaler Temperaturgradienten und in-situ Röntgenabbildung

Kobelt, Ines (Wellmann)
Untersuchung von Temperaturgradient und Strömung bei der ammonothermalen Kristallzüchtung mittels in situ Temperaturmessung im Fluid

Kohler, Julian (Batentschuk)
Aufbau und Charakterisierung eines Alpha-/Beta- Kontaminations-detektors basierend auf Szintillationstechnologie und SiPM-Readout (in Cooperation with Fa. Thermo Fischer, Erlangen)

Kühner, Sebastian (Brabec)
Temperaturabhängigkeit der Degradation von transparenten Silbernanodraht-Elektroden

Marquart, Marcel (Brabec)
Precise automated deposition of solution processed films using the liquid substrate method

Osterrieder, Tobias (Wellmann)
Herstellung und Charakterisierung eines $CuInSe_2$ *Solarzellenabsorbers aus* $Cu_{2-x}Se$ *und* In_2Se_3 *Nanopartikeln*

Römling, Lukas (Brabec)
Novel fatty acid assisted approach for the synthesis of nanosized $SrAl_2O_4:Eu^{2+}$

Volleth, Marco (Brabec)
Synthesis and Purification of Silver Nanowires for Transparent Electrodes

Wagner, Timo (Brabec)
Technologyspecific evaluation of angle-dependent power measurement of PV modules

Zeltner, Johannes (Batentschuk)
Synthesis and surface modification of nanosized $SrAl_2O_4$*:Eu, Sm for photostimulated luminescence nanomarkers*

4. Master Theses

Czajkowski, David (Brabec)
Investigation of Silver Nanowire Inks Focused on their Suitability in Solar Cells

Dreher, Patrick (Brabec)
Detektion von Volumendefekten und Anbindungsfehlern in der Halbleiter-Substrat-Verbindung von leistungselektronischen Modulen - Ultraschallmikroskopie, Röntgen und Thermographie im Vergleich

Einsiedler, Lukas (Brabec, Weber LAP)
Carbon Nanotubes for photodetectors and solar cells

Joisten, Christoph (Brabec)
Accelerated degradation of organic solar cells

Klumpp, Daniel (Wellmann)
Untersuchung der thermoelektrischen Eigenschaften von Graphen-SiC-Partikeln

Köder, Philipp (Brabec)
Solution-Processes Interconnection Layers for Silicon-Perovsite Tandem Solar Cells

Küffner, Johannes (Brabec)
Transfer of room-temperature crystallized perovskite solar cells via solvent-solvent extraction from spin coating in controlled atmosphere to doctor blading in ambient conditions

Lindner, Michael (Wellmann)
Entwicklung eines Versuchsaufbaus zur erzwungenen Kristallisation von Galliumnitrid unter ammonothermalen Bedingungen

Müller, Jonas (Batentschuk)
Vergleichende ökologische Bewertung von Leistungsmodulen auf SiC- und Si-Basis in SINAMICS S120 Frequenzumrichtern mit dem Analyseschwerpunkt werkstoffwissenschaftlicher Zusammenhänge in der Bauelementherstellung

Paleti, Sri Harish Kumare (Brabec)
The role of superoxide formation in photo-oxidation of bulk heterojunction blend films

Pallach, Sandra (Brabec)
Degradationsmechanismen von organischen Photodioden unter Röntgenstrahlung

Polzer, Carsten (Batentschuk)
Synthesis and investigation of temperature dependent luminescence of phosphor blends for thermography in biological objects

Odenwald, **Philipp** (Brabec)
Investigation on the X-Ray Sensitivity of Methyl-Ammonium Lead Iodide Wafer- and Single Crystal-Based Devices

Schöler, Michael (Wellmann)
Characterization of defects in sublimation grown 3C-SiC on 3C-SiC-on-Si seeding layers

Schröppel, Felix (Brabec)
Synthesis of novel phosphors based on Cer^{3+} *doped silicate garnets*

Steiner, Johannes (Wellmann)
Entwicklung einer transparenten Graphen-Elektrode für die Anwendung in fluoreszenten SiC Leuchtdioden

Strohm, Sebastian (Brabec)
Bulk Heterojunction Solar Cells Based on P3HT and the Non-Fullerene Acceptor IDTBR

Thielert, Nick (Wellmann)
Herstellung von Graphen auf SiC-Partikeln für thermoelektrische Anwendungen

Wachsmuth, Josua (Brabec)
Combinatorial Analysis of Organic Solar Cells with Non-Fullerene Electron Acceptors Using High-Throughput Methods

Xu, Junyi (Brabec)
Thermally conductive polymer composites

Zevgitis, Dimitrios (Wellmann)
Aufbau von Prozess- und Messtechnik zur in-situ Röntgenbeugung bei der ammonothermalen Kristallisation von Galliumnitrid

5. Doctoral Theses

Doctoral Theses in Preparation

Abdelhaleem, Soraya (Wellmann, i-MEET)
Determination of Homogeneity of CZTS Absorber Layers Prepared Entirely by Non-vacuum Process for Low cost and Radiation Hardness Solar Cell

Ali, Amjad (Batentschuk, i-MEET)
Developement of phosphors for light conversion in solar panels

Almora Rodríguez, Osbel (Brabec, i-MEET)
Characterization of dynamic response of thin film solar cells

Arzig, Matthias (Wellman, i-MEET)
Systematische Untersuchung der Wachstumskinetik von SiC Einkristallen und Ableitung eines Wachstumsmodells, zur Beschreibung von lateralem Überwachsen von Kristalldefekten und Aufweiten des Kristalldurchmessers

Bechert, Hermann (Brabec,OSRAM OLED GmbH.)
Entwicklung neuartiger OLED-Konzepte

Berger, Christian (Brabec, ZAE)
IT systems and infrastructure for the world wide materials genome

Bogenrieder, Josef (Brabec, ZAE)
Optimierung und Ertragsanpassung von PV-Systemen in einem Smart Grid Netzwerk

Burlafinger, Klaus (Brabec, i-MEET)
Development of a high power illumination setup for accelerated photo-degradation

Carigiet, Fabian (Brabec, Zürcher Hochschule für Angewandte Wissenschaften)
AC PV-Modul: Kontaktlose Stromübertragung von PV-Modulen ins Stromnetz

Channa, Iftikhar (Brabec, ZAE)
Development of solution processed thin film barriers for packaging thin film electronics

Chen, Haiwei (Brabec, i-MEET)
Interface and composition engineering towards stable and efficient organic-inorganic perovskite solar cells

Chen, Shi (Brabec, i-MEET)
Designing and synthesizing novel pervoskite type semiconductors

Chepyga, Liudmyla (Batentschuk, i-MEET)
Developement of new phosphors for high-temperature thermometry

Classen, Andrej (Brabec, i-MEET)
Transport and lifetime investigations of all-carbon solar cells

Dalsass, Manuel (Brabec, ZAE)
Entwicklung optischer Messmethoden zur quantitativen Qualitätsbewertung von PV-Systemen

Doll, Bernd (Brabec, ZAE)
Daylight Electroluminescence of Silicon solar plants

Elia, Jack (Brabec, i-MEET)
TEM Characterization of Solar Cells

Fahlbusch, Lars (Wellmann, i-MEET)
Neue Ansätze beim PVT Wachstum von SiC Einkristallen

Fecher, Frank (Brabec, ZAE)
Simulation of thin-film photovoltaic modules: 2D and 3D spatially resolved electrical and electrothermal finite element calculations

Feroze, Sarmad (Brabec, ZAE)
Building Integration of Organic Photovoltaics

Fischer, Rene (Brabec, Siemens GmbH.)
Hybrid-organische und perovskitische halbleitende metall-organische Absorbermaterialien für die Anwendung in Röntgendetektoren

Gao, Shuai (Brabec, i-MEET)
Core-shell nanoparticles with enhanced properties for smart light management applications: engineering highly efficient upconversion composites

Gao, Yao (Wellmann, i-MEET)
SiC thin film for solar water-to-splitting

Garcia Cerrillo, Jose (Brabec, i-MEET)
Large area and scalable lead-free perovskite modules

Gu, Ening (Brabec, i-MEET)
Technological aspects of solution processed chalcopyrite solar cells

Güldal, Nusret Sena (Brabec, i-MEET)
In-situ monitoring of active layer drying kinetics in organic solar cells

Hassanien, Ayat (Wellmann, i-MEET)
Study of absorbing layer for thin film solar cells based on non-toxic, earth-abundant and low-cost elements

He, Yakun (Brabec, i-MEET)
Solution-processed small molecule solar cells based on non-fullerene acceptors

Heinrichsdobler Armin (Brabec, OSRAM OLED GmbH.)
Tintenstrahldruckprozesse für OLED-Substrat

Hepp, Johannes (Brabec, ZAE)
Spectral and imaging measurement techniques for the purpose of quality control on thin film photovoltaics

Hornich, Julian (Barbec, i-MEET)
Simulations of solar cells with FDTD methods

Kahmann, Simon (Brabec, i-MEET)
Photophysics of nanomaterials for opto-electronic applications

Karl Andre (Brabec, i-MEET)
Bildgebende Charaktersierung von Tandem-Solarzellen

Khanzada, Laraib (Brabec, i-MEET)
Low Cost, Abundant, Non- Toxic and Low Temperature Solution Processable lnorganic Seminconductors for Photovoltaic Applications

Khodamoradi, Hossein (Wellmann, i-MEET)
Modeling of Crystal Growth from the Melt

Killilea, Niall (Heiss, i-MEET)
Inkjet printed phototransistors

Krebs, Kerstin (Brabec, i-MEET)
Transparent, leitfähige Beschichtungen als Elektroden für Touch Panel Displays

Langner, Stefan (Brabec, i-MEET)
Solubility investigation and green formulation based on HSPs

Liu, Chao (Brabec, i-MEET)
A Reliable and Reproducible Intermediate Layer for Solution-processed Organic Tandem Solar Cells

Maisch, Philipp (Brabec, ZAE)
Printing studies on layers of organic solar cells for upscaling and solar module manufacturing

Makhdoom, Atif (Brabec, ZAE)
Low temperature route for the Development of Photovoltaic and optoelectronic devices using Silicon nanoparticles

Mashkov, Oleksandr (Heiss, i-MEET)
Organic pigment nanocrystals

Meng, Wei (Brabec, i-MEET)
Vacuum free electrode for printed solar cells

Montenegro Benavides, Cindy Alexandra (Brabec, Siemens Healthcare GmbH.)
Optimization of Organic Photodetectors from the Visible to the Near Infrared Spectra for Industrial Applications

Neubauer, Georg (Wellmann, i-MEET)
Computertomographie bei der Kristallzüchtung

Perea Ospina, Jose Dario (Brabec, i-MEET)
Predicting the Microstructure Stability in Photovoltaic Polymer-Fullerene Blends Using Figure of Merit

Pröll Markus (Brabec, ZAE)
Optimization of a CPC PVT Hybrid Solar Collector and Exergy Maximization

Ramirez Quiroz, César Omar (Brabec, i-MEET)
Solubility investigation based on COSMO-RS approach

Richter, Moses (Brabec, i-MEET)
Transport properties of organic / inorganic hybrid composites

Sauermann, Tobias (Brabec,Belectric GmbH.)
Degradation Mechanisms in Organic Solar Cells

Schimmel, Saskia (Wellmann, i-MEET)
In situ Visualisierung des ammonothermalen Kristallisationsprozesses mittels Röntgenmesstechnik

Schöler, Michael (Wellmann, i-MEET)
Doping of cubic silicon carbide

Schuh, Philipp (Wellmann, i-MEET)
Sublimation Epitaxy of 3C-SiC

Schuster, Matthias (Wellmann, i-MEET)
CISe Thin Film Solar Cells with Novel Materials

Schwamb, Philipp (Brabec, OSRAM OLED GmbH.)
Flexible white OLEDs

Shen, Yilei (Brabec, i-MEET)
Lösungsprozessierung für die semitransparenten Elektroden der organischen Leuchtdioden

Shrestha, Shreetu (Brabec, i-MEET)
Methylammonium Lead Iodide Perovskite for Direct X-ray Detection

Stegner, Christoph (Brabec, ZAE)
Integration elektrochemischer Energiespeicher ins Verteilnetz

Steiner, Johannes (Wellmann, i-MEET)
Dislocation networks in Silicon Carbide

Tam, Kai Cheong (Brabec, ZAE)
Ink-jet printing on organic imaging device

Tang, Xiaofeng (Brabec, i-MEET)
In-situ degradation and FTIR based analysis of conjugated semiconductors with relevance for organic electronic applications

Wilhelm, Martin (Wellmann, i-MEET)
SiGeC Hetero-Epitaxie

Wittmann, Stephan (Brabec, ZAE)
Entwicklung und Optimierung von Zell- und Modulkonzepten für Dünnschicht-Silizium-Solarzellen auf Fremdsubstraten

Xie, Chen (Brabec, i-MEET)
Green formulation based on polymeric nanoparticles

Xu, Junyi (Brabec, i-MEET)
Development and characterization of highly transparent electrode composites and their application in photovoltaics

YousefiAmir, AminAbbas (Heiss, i-MEET)
Inkjet printed nanocrystal devices

Zweschke, André (Wellmann, i-MEET)
Modellierung der Absorberschichtbildung von CIS-Solarzellenmaterialien

Doctoral Theses Completed

13.01.2017
Spyropoulos, George (Brabec, ZAE)
Smart Device Fabrication Strategies for Solution Processed Solar Cells
Intelligente Herstellungsstrategien für lösungsprozessierte Solarzellen

27.01.2017
Ke, Lili (Brabec i-MEET)
A Series of Novel Silicon Phthalocyanines /Naphthalocyanine as Near Infrared Sensitizers in Organic Ternary and Quaternary Solar Cells
Eine Reihe von neuartigen Silizium-Phthalocyaninen/ Naphthalocyaninen als Nahinfrarot-Sensibilisatoren in ternären und quaternären organischen Solarzellen

30.03.2017
Bronnbauer, Carina (Brabec, i-MEET)
Printed Dielectric Mirrors and their Application in Organic Electronics
Gedruckte dielektrische Spiegel und deren Anwendung in organischer Elektronik

05.04.2017
Riecke, Arne (Brabec, ZAE)
Thermische Umwandlung dünner Silizium-Schichten

24.05.2017
Kötter, Tobias (Brabec, Siemens GmbH.)
Hochleistungsdichte Phasenwechsel-Komposit-Materialien für das Thermomanagement von elektrotechnischen Systemen

12.06.2017
Hou Yi (Brabec, i-MEET)
Rational Interfaces Design of Efficient Organic-inorganic Hybrid Perovskite Solar Cells
Rationales Design von Ladungsträgerextraktionsschichten für effiziente organisch-anorganische Hybrid-Perovskit-Solarzellen

20.06.2017
Levchuk, Ivegen (Batentschuk, i-MEET)
Design and Optimization of Luminescent Semiconductor Nanocrystals for Optoelectronic Applications
Erstellung und Optimierung von lumineszierenden Halbleiter-Nanokristallen für optoelektronische Anwendungen

22.06.2017
Gasparini, Nicola (Brabec, i-MEET)
Controlling Charge Carrier Recombination in Ternary Organic Solar Cells
Unterdrückung von Ladungsträgerrekombination in ternären organischen Solarzellen

19.12.2017
Zhang, Chaohong (Brabec, i-MEET)
Influence of Microstructure on Thermo- and Photostability in Organic Bulk-Heterojunction Solar Cell
Einfluss der Mikrostruktur auf die Thermo- und Lichtstabilität in organischen Bulk-Heterojunction Solarzellen

6. Awards

Ameri, Tayebeh

Bavarian Equal Opportunities Sponsorship – Förderung von Frauen in Forschung und Lehre (FFL), FAU

Emerging Talents Initiative (ETI) Funding for Outstanding Postdoctoral Researchers

The ETI supports excellent junior researchers to start building their reputation in a competitive research environment by submitting a first research proposal. Winning an ETI award is a prestigious acknowledgement of a young academic´s research track and makes us curious and excited to looking forward to Tayebeh's next achievements!

Bavaria California Technology Center Fond (BaCaTeC)
Tayebeh received the initial funding of new projects, especially,those which support the exchange of scientists in reference to the projects between Bavaria and California.

Brabec, Christoph

Honored as ***Highly Cited Researcher*** (Web of Science, 7th time in a row)

Heinrichsdobler, Armin

Best Student Paper Award winner for "*Inkjet-printed polymer-based scattering layers for enhanced light out coupling from top-emitting organic light-emitting diodes*" (see Conference Proceedings)
Conference SPIE Optics & Photonics 2017, San Diego, California, United States

Heumüller, Thomas

STAEDTLER Stiftung
Dissertation Price 2017

Thomas Heumüller received the highly endowed doctoral dissertation prize of the Stadtler Stiftung Nürnberg for his outstanding academic achievement.

Hou, Yi

Outstanding Student´s Abroad in 2017

The international PhD committee with Prof Nazeeruddin (from EPFL), Rainer Hock (Chair for Crystallography), Wolfgang Heiss and Christoph Brabec (both i-MEET) acknowledged Yi´s achievements with the grade “Very Good”. In parallel, the Chinese Government acknowledged Yi´s excellent performance over the last years and awarded him the “Outstanding Student´s Award 2017” in a ceremonial act in Berlin.

Li, Ning

Younge Scientist Bronze Award IUMRS-ICAM 2017

IUMRS-ICAM2017
Young Scientist Awards

BRONZE AWARD

Yabing QI
Okinawa Institute of Science and Technology Graduate University

Ning LI
Friedrich-Alexander University Erlangen-Nürnberg

Ning won the “Younge Sceintist Bronze Award” at the IUMRS-ICAM 2017. MRS-Japan organized the conference in Kyoto, Japan during the period of August 27 to September 1, 2017. The International Conference of Advanced Materials (ICAM). It is one of the best materials conferences on advanced materials concepts and composes multiple symposia in one.
About the award: The “Young Scientist Awards” in IUMRS-ICAM 2017 consists of gold, silver, and bronze awards, and are intended to honor and encourage outstanding young scientists, who have contributed to IUMRS-ICAM 2017 as presenters, and whose academic achievements and current research works demonstrate a high level of excellence and distinction. The IUMRS-ICAM 2017 committees seek to recognize young scientists with outstanding and exceptional abilities showing great potentials toward significant future progress in a variety of material related research fields.

Emerging Talents Initiative (ETI) Funding for Outstanding Postdoctoral Researchers

The ETI supports excellent junior researchers to start building their reputation in a competitive research environment by submitting a first research proposal. Winning an ETI award is a prestigious acknowledgement of a young academic´s research track and makes us curious and excited to looking forward to Ning´s next achievements!

7. Publications (Full Papers and Conference Proceedings)

Full Papers

A. Ali, L.S. Khanzada, A. Hashemi, C. Polzer, A. Osvet, C. Brabec, M. Batentschuk
Optimization of synthesis and compositional parameters of magnesium germanate and fluoro-germanate thermographic phosphors
Journal of Alloys and Compounds ***734****, pp. 29-35, 2018, Online 2017*
DOI: 10.1016/j.jallcom.2017.10.259

Derya Baran, Sachetan Tuladhar, Solon P. Economopoulos, Marios Neophytou, Achilleas Savva, Grigorios Itskos, Andreas Othonos, Donal D.C. Bradley, Christoph J. Brabec, Jenny Nelson, Stelios A. Choulis
Photovoltaic limitations of BODIPY:fullerene based bulk heterojunction solar cells
Synthetic Metals ***226****, pp.25-30, 2017*
DOI: 10.1016/j.synthmet.2017.01.006

Baran, D., Ashraf, R.S., Hanifi, D.A., Abdelsamie, M., Gasparini, N., Röhr, J.A., Holliday, S., Wadsworth, A., Lockett, S., Neophytou, M., Emmott, C.J.M., Nelson, J., Brabec, C.J., Amassian, A., Salleo, A., Kirchartz, T., Durrant, J.R., McCulloch, I.
Reducing the efficiency–stability–cost gap of organic photovoltaics with highly efficient and stable small molecule acceptor ternary solar cells
Nature Materials ***16(3)****, pp. 363-369, 2017, Online 2016*
DOI: 10.1038/nmat4797

J. Bogenrieder, M. Hüttner, P. Luchscheider, J. Hauch, C. Camus, C.J. Brabec
Technology-specific yield analysis of various photovoltaic module technologies under specific real weather conditions
Progress in Photovoltaics Research and Applications ***26****, 74-85, 2018, Online 2017*
DOI: 10.1002/pip.2921

Carina Bronnbauer, Arne Riecke, Marius Adler, Julian Hornich, Gerhard Schunk, Christoph J. Brabec, and Karen Forberich
Printing of Large-Scale, Flexible, Long-Term Stable Dielectric Mirrors with Suppressed Side Interferences
Advanced Optical Materials ***6(4)****, Article number 1700518, 9 pages, 2018, Online 2017*
DOI: 10.1002/adom.201700518

Claudia Buerhop, Tobias Pickel, Tirth Patel, Frank W. Fecher, Cornelia Zetzmann, Christian Camus, Jens Hauch, Christoph J. Brabec
Analysis of inhomogeneous local distribution of Potential induced degradation at a rooftop photovoltaic installation
IET Renewable Power Generation ***11(10)****, pp. 1253-1260, 2017*
DOI: 10.1049/iet-rpg.2017.0105

Claudia Buerhop, Sven Wirsching, Andreas Bemm, Tobias Pickel, Philipp Hohmann, Monika Nieß, Christian Vodermayer, Alexander Huber, Bernhard Glück, Julia Mergheim, Christian Camus, Jens Hauch, Christoph J. Brabec
Evolution of cell cracks in PV-modules under field and laboratory conditions
*Progress in Photovoltaics Research and Applications **26**, 261-272, 2018, Online 2017*
DOI: 10.1002/pip.2975

Claudia Buerhop-Lutz, Tobias Pickel, Andreas Bemm, Christian Vodermayer, Bernhard Glück, Alexander Huber, Christian Camus, Jens Hauch, Christoph Brabec
Zellrisse - nur halb so schlimm?
pv magazine, November 2017

Tiantian Cao, Ning Chen, Guangxin Liu, Yingbo Wan, Jose Dario Perea, Yijun Xia, Zhaowei Wang, Bo Song, Ning Li, Xiaohong Li, Yi Zhou, Christoph J. Brabec and Yongfang Li
Towards a full understanding of regioisomer effects of indene-C60 bisadduct acceptors in bulk heterojunction polymer solar cells
*Journal of Materials Chemistry A **5(21)**, pp. 10206-10219, 2017*
DOI: 10.1039/c7ta01665d

Shi Chen, Yi Hou, Haiwei Chen, Xiaofeng Tang, Stefan Langner, Ning Li, Tobias Stubhan, Ievgen Levchuk, Ening Gu, Andres Osvet, and Christoph J. Brabec
Exploring the Stability of Novel Wide Bandgap Perovskites by a Robot Based High Throughput Approach
Advanced Energy Materials - Communication 8, Article number 1701543, 8 pages, Online 2017
DOI: 10.1002/aenm.201701543

Liudmyla M. Chepyga, Andres Osvet, Christoph J. Brabec, Miroslaw Batentschuk
High-temperature thermographic phosphor mixture YAP/YAG:Dy^{3+} and its photoluminescence properties
*Journal of Luminescence **188**, pp. 582-588, 2017*
DOI: 10.1016/j.jlumin.2017.04.070

Christos L. Chochos, Sofia Drakopoulou, Athanasios Katsouras, Benedetta M. Squeo, Christian Sprau, Alexander Colsmann, Vasilis G. Gregoriou, Alex-Palma Cando, Sybille Allard, Ullrich Scherf, Nicola Gasparini, Negar Kazerouni, Tayebeh Ameri, Christoph J. Brabec, Apostolos Avgeropoulos
Beyond Donor-Acceptor (D-A) Approach: Structure-Optoelectronic Properties-Organic Photovoltaic Performance Correlation in New D-A_1-D-A_2 Low-Bandgap Conjugated Polymers
Macromolecular Rapid Communications, Article in press, Online 2017
DOI: 10.1002/marc.201600720

Chochos, C.L., Katsouras, A., Gasparini, N., Koulogiannis, C., Ameri, T., Brabec, C.J., Avgeropoulos, A.
Rational Design of High-Performance Wide-Bandgap (≈2 eV) Polymer Semiconductors as Electron Donors in Organic Photovoltaics Exhibiting High Open Circuit Voltages (≈1 V)
*Macromolecular Rapid Communications, **38(2)**, Article number 16006, pages 10, 2017, Online 2016*
DOI: 10.1002/marc.201600614

Christos L. Chochos, Nicolas Leclerc, Nicola Gasparini, Nicolas Zimmerman, Elisavet Tatsi, Athanasios Katsouras, Dimitrios Moschovas, Efthymis Serpetzoglou, Ioannis Konidakis, Sadiara Fall,e Patrick Lèvêque, Thomas Heiser, Michael Spanos, Vasilis G. Gregoriou, Emmanuel Stratakis, Tayebeh Ameri, Christoph J. Brabec and Apostolos Avgeropoulos
The role of chemical structure in indacenodithienothiophene-alt benzothiadiazole copolymers for high performance organic solar cells with improved photo-stability through minimization of burn-in loss
*Journal of Materials Chemistry A **5**, Article number 25064, 13 pages, 2017*
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Suppression of Thermally Induced Fullerene Aggregation in Polyfullerene-Based Multiacceptor Organic Solar Cells
*ACS Applied Materials and Interfaces **9(12)**, Article number 1700007, pp. 10971-10982s, 2017*
DOI: 10.1021/acsami.7b00401

Xiaoyan Du, Xuechen Jiao, Stefanie Rechberger, JoséDarío Perea, Markus Meyer, Negar Kazerouni, Erdmann Spiecker, Harald Ade, Christoph J. Brabec, Rainer H. Fink, and Tayebeh Ameri
Crystallization of Sensitizers Controls Morphology and Performance in Si-/C-PCPDTBT-Sensitized P3HT:ICBA Ternary Blends
*Macromolecules **50(6)**, pp. 2415-2423, 2017*
DOI: 0.1021/acs.macromol.6b02699

Du, X., Lytken, O., Killian, M.S., Cao, J., Stubhan, T., Turbiez, M., Schmuki, P., Steinrück, H.-P., Ding, L., Fink, R.H., Li, N., Brabec, C.J.
Overcoming Interfacial Losses in Solution-Processed Organic Multi-Junction Solar Cells
*Advanced Energy Materials 7**(5)**, 10 pages, 2017*
DOI: 10.1002/aenm.201601959

Nicola Gasparini, Luca Lucera, Michael Salvador, Mario Prosa, George D. Spyropoulos, Peter Kubis, Hans Joachim Egelhaaf, Christoph J. Brabec and Tayebeh Ameri
High performance ternary organic solar cells with thick active layer exceeding 11% efficiency
Energy & Environmental Science 10(4), pp. 885-892, 2017
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Polymer: Nonfullerene Bulk Heterojunction Solar Cells with Exceptionally Low Recombination Rates
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Nicola Gasparini, Michael Salvador, Sebastian Strohm, Thomas Heumueller, Ievgen Levchuk, Andrew Wadsworth, James H. Bannock, John C. de Mello, Hans-Joachim Egelhaaf, Derya Baran, Iain McCulloch, and Christoph J. Brabec
Burn-in Free Nonfullerene-Based Organic Solar Cells
*Advanced Energy Materials **7(19)**, Article number 1700770, 7 pages, 2017*
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Indacenodithienothiophene-Based Ternary Organic Solar Cells
*Frontiers in Energy Research **4**, Article 40, 9 pages, 2017*
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Acenequinocumulenes: Lateral and vertical π-extended analogs of tetracyanoquinodimethane (TCNQ)
*Chemistry - A European Journal **23(70)**, pp. 17829-17835, 2017*
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In situ characterization methods for evaluating microstructure formation and drying kinetics of solution-processed organic bulk-heterojunction films
*Journal of Materials Research **32(10)**, pp. 1855-1879, 2017*
DOI: 10.1557/jmr.2017.190

Fei Guo, Andre Karl, Qifan Xue, Kai Cheong Tam, Karen Forberich and Christoph J Brabec
The fabrication of color-tunable organic light-emitting diode displays via solution processing
*Light: Science & Applications **6**, e17094, 9 pages, 2017*
DOI: 10.1038/lsa.2017.94

Amir Hashemi, Gordana Jovicic, Miroslaw Batentschuk, Christoph J Brabec and Andreas Vetter
Contactless temperature determination using dual-channel lock-in phosphor thermometry
*Measurement Science and Technology **28(2)**, Article number 027001, 2017*
DOI: 10.1088/1361-6501/aa5010

A. Hashemi, J. Gast, A. Ali, A. Osvet, M. Batentschuk, C. J. Brabec
Surface thermography using dual channel imaging based on the blue and red emission of $Ba_3MgSi_2O_8:Eu^{2+}$, Mn^{2+}
*Measurement Science and Technology **28**, Article number 125205, 10 pages, 2017*
DOI: 10.1088/1361-6501/aa8fb7

Jonas Häusler, Saskia Schimmel, Peter Wellmann, and Wolfgang Schnick
Ammonothermal Synthesis of Earth-Abundant Nitride Semiconductors $ZnSiN_2$ and $ZnGeN_2$ and Dissolution Monitoring by In Situ X-ray Imaging
*Chemistry - A European Journa **23(50)**, pp. 12275-12282, 2017*
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Pinhole-Free Inkjet Printing Strategies for Organic Electronics
*Advanced Materials Technologies **2(12)**, Article no. 1700166, 9 pages, 2017*
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Felix Hermerschmidt, Achilleas Savva, Efthymios Georgiou, Sachetan M. Tuladhar, James R. Durrant, Iain McCulloch, Donal D. C. Bradley, Christoph J. Brabec, Jenny Nelson, and Stelios A. Choulis
Influence of the Hole Transporting Layer on the Thermal Stability of Inverted Organic Photovoltaics Using Accelerated-Heat Lifetime Protocols
*ACS applied materials & interfaces **9(16)**, Article 40, pp. 14136-14144, 2017*
DOI: 10.1021/acsami.7b01183

Ellen Hertle, Liudmyla Chepyga, Miroslaw Batentschuk, Lars Zigan
Influence of codoping of YAG:Dy for high temperature phosphor thermometry
*Journal of Luminescence **182**, pp. 200-207, 2017*
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Suppression of Hysteresis Effects in Organohalide Perovskite Solar Cells
*Advanced Materials Interfaces **4(11)**, Article number 1700007, 9 pages, 2017*
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A generic interface to reduce the efficiency-stability-cost gap of perovskite solar cells
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Excited-State Interaction of Semiconducting Single-Walled Carbon Nanotubes with Their Wrapping Polymers
*Journal of Chemistry Letters **8(22)**, pp. 5666-5672, 2017*
DOI: 10.1021/acs.jpclett.7b02553

Simon Kahmann, Mykhailo Sytnyk, Nadine Schrenker, Gebhard J. Matt, Erdmann Spiecker, Wolfgang Heiss, Christoph J. Brabec, and Maria A. Loi
Revealing Trap States in Lead Sulphide Colloidal Quantum Dots by Photoinduced Absorption Spectroscopy
*Advanced Electronic Materials **4(1)**, Article number 1700348, 7 pages, 2017*
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Lili Ke, Nicola Gasparini, Jie Min, Hong Zhang, Matthias Adam, Stefanie Rechberger, Karen Forberich, Chaohong Zhang, Erdmann Spiecker, Rik R. Tykwinski, Christoph J. Brabec and Tayebeh Ameri
Panchromatic ternary/quaternary polymer/fullerene BHJ solar cells based on novel silicon naphthalocyanine and silicon phthalocyanine dye sensitizers
*Journal of Materials Chemistry A **5(6)**, pp. 2550-2562, 2017*
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Triphenylamine-Based Push-Pull Molecule for Photovoltaic Applications: From Synthesis to Ultrafast Device Photophysics
*Journal of Physical Chemistry C **121(12)**, pp. 6424-6435, 2017*
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Optimization of synthesis and compositional parameters of magnesium germanate and fluoro-germanate thermographic phosphors

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Various documented formulations of magnesium germanate and flouro-germanate were synthesized by conventional solid state method at various temperatures to find out optimal synthesis conditions for maximum luminescence intensity. Relative efficiency of luminescence intensity and thermal stability of luminescence of these formulations is then discussed with respect to the commercially available phosphor. $Mg_{28}Ge_{7.5}O_{38}F_{10} : Mn^{4+}$ was found to be the most efficient when synthesized at 1150 °C in air and has a comparable efficiency with respect to commercial sample. Photoluminescence intensity with increasing temperature was measured till 500 °C; the samples showed persistent emission till 300 °C. Relatively, samples with MgF_2 give stronger emission at high temperatures if added in proper ratio.

1. Introduction

Magnesium fluoro-germanate is an efficient deep red phosphor commonly used in high-pressure mercury lamps for color correction due to its intense deep red 658 nm luminescence emission at temperatures up to 300 °C [1–3]. It is also used in low-pressure mercury lamps to achieve high color rendering index (CRI) [4,5]. Other uses include red light phototherapy equipment and plant growth lamps with a combination of blue or UV LEDs [6]. Several researchers reported the use of this phosphor for thermographic measurements ranging from 4 K to 1150 K [7–13]. Seyfried used this phosphor for surface thermometry in the afterburner of an aircraft engine using the decay time technique [10]. Omrane et al. used the ratio of luminescence peaks of this phosphor (intensity ratio method) for thermal imaging of single liquid droplets [14]. They also used the decay time method for 2D measurement of the temperature of combustible and noncombustible surfaces by using multiple CCD cameras [11]. Omrane et al. used the same phosphor for the surface temperature measurement of decomposing construction materials by using decay time method [12]. As this phosphor can be excited by the standard blue LEDs, it has been proved to be suitable for making warm white LED [15].

The first description of magnesium germanate phosphor is by Williams in 1947 [16] who patented the phosphor in the next year [17]. He prepared this phosphor as Mg_4GeO_6 doped with 1% Mn as optimal concentration by solid state method at a temperature between 1100 °C and 1200 °C. Stanley H. Patten showed that the fine structure of emission is unique in this phosphor and not known in any other Mn activated phosphor at that time [18]. He also measured the variation of peak intensities with changing temperature. F. A. Kroeger argued that the fine structure of emission is due to the presence of Mn in tetravalent instead of divalent state, as previously thought [19]. Later, Luke Thorington found that

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Photovoltaic limitations of BODIPY:fullerene based bulk heterojunction solar cells

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ABSTRACT

The photovoltaic performance of blends of a series of 4,4′-Difluoro-4-bora-3a,4a-diaza-s-indacenes)-based (BODIPY) conjugated polymers donors with fullerene electron acceptors is investigated. Despite the high Voc values observed, solar cell device yields relatively low power conversion efficiencies. Our study takes into account the materials' structure-property relationship, light harvesting capabilities, charge transport, collection properties and morphological characteristics to elucidate factors affecting the photovoltaic performance in this class of polymers. We show that elimination of low molecular weight species and suitable electrodes for hole collection can be used to overcome some of the observed limitations on photovoltaic performance.

1. Introduction

During the last decade, bulk heterojunction solar cells are attracting great scientific interest because of the potential for low fabrication cost and light weight. One of the niche markets for commercializing this technology is the ease of deposition on flexible substrates. All these features offer new advantages and functionalities in comparison to state of the art inorganic photovoltaics. Power conversion efficiencies (PCE) as high as 12%, have been achieved [1–4] through optimization of device architecture and material engineering. While solar cell performance has been improved via thermal and vapor annealing processes, the use of additives [5] and interface optimization for charge carrier transportation and collection [6–9], conjugated low band gap ($Eg < 2$ eV) polymers with better solar harvesting and transport properties than existing donor materials, are expected to further improve PCEs [10,11]. To do so, there are two synthetic routes that still allow a functional energy level alignment with electron acceptor's LUMO level. Either, by lowering the electron donor's LUMO level or raising its HOMO level, in respect to the vacuum level. The former may reduce the interfacial exciton dissociation ability of the system and the latter will increase polymer oxidation and degradation potential and reduce open circuit voltage (V_{oc}) of the device. In this publication we describe a class of fluorescent 4,4′-Difluoro-4-bora-3a,4a-diaza-s-indacenes conjugated polymers (BODIPY) -a novel electron donor candidate for organic photovoltaics achieving high photovoltage values. BODIPY dyes have recently attracted considerable attention owed mainly to their interesting optical properties [12,13]. Despite being introduced a few years ago, the synthetic versatility offered by this class of molecules paved the way for a large number of small molecule light harvesting moieties for solar cells [14–16], donor-acceptor hybrids, either with fullerenes [17,18] or with other molecular electron acceptors [19,20], which is a testament to their interest and potential. Polymers incorporating the BODIPY moiety, however, are still scarce and reports on solar cells with BODIPY -based polymers as the electron donor yield relatively low efficiencies [21,22], attributed perhaps to low charge carrier mobilities [23]. The present work aims to add to the family of

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Reducing the efficiency–stability–cost gap of organic photovoltaics with highly efficient and stable small molecule acceptor ternary solar cells

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Technological deployment of organic photovoltaic modules requires improvements in device light-conversion efficiency and stability while keeping material costs low. Here we demonstrate highly efficient and stable solar cells using a ternary approach, wherein two non-fullerene acceptors are combined with both a scalable and affordable donor polymer, poly(3-hexylthiophene) (P3HT), and a high-efficiency, low-bandgap polymer in a single-layer bulk-heterojunction device. The addition of a strongly absorbing small molecule acceptor into a P3HT-based non-fullerene blend increases the device efficiency up to 7.7 ± 0.1% without any solvent additives. The improvement is assigned to changes in microstructure that reduce charge recombination and increase the photovoltage, and to improved light harvesting across the visible region. The stability of P3HT-based devices in ambient conditions is also significantly improved relative to polymer:fullerene devices. Combined with a low-bandgap donor polymer (PBDTTT-EFT, also known as PCE10), the two mixed acceptors also lead to solar cells with 11.0 ± 0.4% efficiency and a high open-circuit voltage of 1.03 ± 0.01 V.

At present, the materials used in organic photovoltaics (OPV) are dominated by fullerene acceptors in combination with low-bandgap donor polymers which typically require complex and multi-step syntheses[1–5]. However, the commercialization of OPV requires the availability of inexpensive materials in large quantities, such as poly(3-hexylthiophene) (P3HT). P3HT is readily scalable via flow or micro-reactor synthesis, even using 'green' solvents, whilst retaining a high degree of control over molecular weight and regio-regularity[6]. The P3HT:60PCBM blend exhibits one of the most robust microstructures within OPV[7–9]. However, it has a limited open-circuit voltage (V_{oc}) and short-circuit current (J_{sc}) in photovoltaic devices[10]. We have recently shown that solar cells using an alternative small molecule non-fullerene acceptor (NFA), IDTBR, when mixed with P3HT, can achieve power conversion efficiencies of up to 6.4% (ref. 11). These results have revived interest in the use of P3HT for high-performance devices and non-fullerene acceptors[12–18]. The combination of stability, cost and performance for P3HT:NFA devices make them a compelling choice for commercialization of OPV compared to devices using fullerenes, for which the high costs and energy involved are prohibitive for large-scale production.

Recently, multi-component heterojunctions (ternary or more) have emerged as a promising strategy to overcome the power conversion efficiency (PCE) bottleneck associated with binary bulk-heterojunction (BHJ) solar cells[3,4,19–24]. However, simultaneous increase in the V_{oc}, J_{sc} and fill factor (FF) is a challenge in the ternary approach because of the trade-off between photocurrent and voltage[23,25,26]. Reports show ternary blends using fullerene acceptors, where the V_{oc} is increased using a second acceptor (A_2) with a higher electron affinity (EA) than A_1 (refs 23,27–29); however, very few examples of two-acceptor ternary blend devices could surpass the overall efficiency of their respective binary blends[24,30,31]. Therefore, the majority of studies on ternary solar cells have focused on multi-polymer donor:acceptor blends[19,23,27–29]. However, the mixing of two polymers is more complicated due to both a lack of entropic driving force for mixing, and the potential for strong intermolecular attractions between polymer chains[32]. Therefore, a ternary approach, wherein small molecule acceptors are mixed in a donor:multi-acceptor blend ($D:A_1:A_2$, where D is the donor polymer, A_1 is the primary acceptor and A_2 is a second acceptor), has the potential to offer morphological advantages. Small molecule NFAs have already reached >10% PCEs in binary BHJ devices with low-bandgap donor polymers[33]; however, their potential in multi-component junctions has not yet been explored.

Here, we demonstrate highly efficient solar cells by both combining P3HT with two NFAs in a ternary blend, as well as extending this approach to utilize a high-efficiency, low-bandgap polymer PCE10, in place of P3HT. Through optimizing the acceptor

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WILEY PROGRESS IN PHOTOVOLTAICS

APPLICATION

Technology-specific yield analysis of various photovoltaic module technologies under specific real weather conditions

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Abstract

In the presented paper, we introduce an approach to rate the performance of modules under specific real weather conditions, since solar modules are rated according to standard test conditions which do not give evidence of the performance under real outdoor conditions. Therefore, we categorize the daily weather at a photovoltaic test site into 7 different climatic-day classifications and multiple cloud scenarios. Two different approaches to evaluate the cloud conditions were investigated. Furthermore, we use the developed approach to rate the performance of 8 different commercially available photovoltaic modules that have been installed and measured in Germany. The evaluation shows that module properties (eg, temperature coefficient, spectral response, and mechanical construction) have a major influence on the performance of photovoltaic modules under different weather conditions.

KEYWORDS
climate, outdoor, performance, photovoltaics, weather, yield analysis

1 | INTRODUCTION

The International Energy Agency reported that at the end of the year 2015, about 227 GWp of photovoltaics (PV) were installed worldwide and about 1.3% of the electricity worldwide was produced by PV.[1] To accomplish the goals of the Paris Agreement,[2] the expansion of renewable energies production is mandatory. Photovoltaics is a key technology in the field of electricity production to reduce greenhouse gas emission and can be installed globally under different climatic conditions.

However, the performance of PV modules is exclusively rated according to the power stated in the data sheet which is determined under standard test conditions (STC; 1000 W/m^2, AM1.5, 25°C). Also, the measurements at normal operating cell temperature (800 W/m^2, AM1.5, 20°C, 1 m/s), the temperature coefficient, and in some data sheets, the low-light efficiency at 200 W/m^2 just give an incomplete insight of the performance of PV modules under different weather and climatic conditions. Nowadays, various PV technologies are available; each of them exhibiting different optical, electrical, and thermal properties. Hence, an investigation to rate the performance of different module technologies under specific real weather conditions is required to asses the suitability of a given PV technology for a given climate, ie, location.

In existing studies, mostly specific module technologies were investigated under outdoor and/or laboratory conditions according to their specific yearly or seasonal yield,[3-7] ageing behaviour,[8-11] behaviour on spectral or thermal influences,[12-15] or light soaking effects.[16,17] Therefore, we present an approach to categorize the weather and cloud conditions at a specific site to rate the specific outdoor performance of PV modules. Furthermore, we use the developed approach to investigate 8 different commercially available modules in the period from August 1, 2015 to July 31, 2016. We also discuss the influence of different module parameters (eg, low light performance and temperature coefficient) as the presumable root causes for the performance differences under various weather scenarios.

At first, we describe the test site as well as the data acquisition system followed by the determination of the different weather scenarios. Afterwards, we present and discuss the results of the investigation and sum up in a conclusion and present an outlook on future research activities.

2 | PHOTOVOLTAICS TEST SITE

The measurement equipment as well as the investigated PV modules were installed at the ZAE Bayern test site in Arzberg, Germany.

ADVANCED OPTICAL MATERIALS
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Printing of Large-Scale, Flexible, Long-Term Stable Dielectric Mirrors with Suppressed Side Interferences

*Carina Bronnbauer, Arne Riecke, Marius Adler, Julian Hornich, Gerhard Schunk, Christoph J. Brabec, and Karen Forberich**

Dielectric mirrors are wavelength-selective mirrors which are based on thin film interference effects. Their optical band can precisely be adjusted in width, position, and reflectance by the refractive index of the applied materials, the layers' thicknesses, and the amount of deposited layers. Nowadays, they are a well-known light management tool for efficiency enhancement in, for example, semitransparent organic solar cells (OSCs) and light guiding in organic light-emitting diodes (OLEDs). However, most of the dielectric mirrors are still fabricated by lab-scale techniques such as spin-coating or physical vapor deposition under vacuum. Large-scale, fully printed (maximum 20 × 20 cm^2) dielectric mirrors with adjustable reflectance characteristics are fabricated, using temperatures of maximum 50 °C and alcohol-based inks. According to the moderate processing conditions they can be easily deposited not only on rigid glass substrates but also on flexible foils. They show high stability against humidity, light irradiation, and temperature, positioning themselves as good candidates for applications in OLEDs and OSCs. Eventually, by simulations and experiments it is verified that a moderate degree of variations in layer thickness and surface roughness can suppress side interference fringes, while not impacting the main transmittance minimum or the main reflection maximum, respectively.

1. Introduction

Dielectric mirrors (also known as 1D photonic crystals, Bragg mirrors, or dichroic filters) belong to the group of multilayer interference filters and enable to engineer light propagation in a certain wavelength regime not by absorption, but due to reflection. They consist of a stack of alternately aligned transparent layers of high and low refractive index (n_{high}, n_{low}) dielectric materials. The minimum of transmittance (λ_0), the width, and the amplitude of the optical band are determined by stack alignment, layer thickness, and refractive index contrast between both applied materials. However, the angle of incidence and the polarization of the incident light may impact these characteristics, too. To achieve maximum reflection at normal light incidence, each layer thickness of the stack (d_{high}, d_{low}) has to fulfill the so-called Bragg condition

$$n_{\text{high}} \times d_{\text{high}} = n_{\text{low}} \times d_{\text{low}} = \lambda_0 / 4 \qquad (1)$$

Nowadays, the research in the field of dielectric mirrors is mainly driven by their very broad application fields. Dielectric mirrors do not only serve as a light management tool for radiation shieldings, anti-reflection coatings, efficiency enhancement in semitransparent photovoltaics, light guiding in emitting devices, but also as sensors or encapsulants.[1–6]

The discovery of dielectric mirrors started along with the theoretically description of interference effects at thin films in the early 20th century. Quickly realizing their great potential, the first anti-reflection coatings fabricated by physical vapor deposition of inorganic materials for rifle-scopes and binoculars had already been established during the Second World War.[7] Next, and based on the development of fully solution processed oxide coatings via the sol-gel method by the company Jenaer Glaswerk Schott & Gen., the first dip-coated optical multilayer stacks appeared on the market in the 1960s.[8] In the following years, this concept also became well known in the scientific community, while mainly SiO$_2$ and TiO$_2$ ceramics were used for fabrication since those materials provide the largest refractive index

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Analysis of inhomogeneous local distribution of potential induced degradation at a rooftop photovoltaic installation

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Abstract: Potential induced degradation (PID) of photovoltaic (PV) modules is one of the frequently observed failures in PV installations nowadays. This study investigates the inhomogeneous and complex PID generation on rooftop installations on industrial buildings as well as its impact on the module performance. The PID development is exemplarily presented for a 314kWp PV-plant installed in the Atlantic coastal climate. Due to the complex plant geometry and resulting irradiation situation the existence of PID could not be identified based on the annual yield data. By Infrared imaging PID was clearly identified. Evaluating historic monitoring data, the impact of PID on the string and plant performance could be quantified. A linear correlation between the defect ratio and the performance rate as well as the degradation loss rate could be formulated.

1 Introduction

Potential induced degradation (PID) of photovoltaic (PV) modules is a failure mode that has become more prevalent during the last years. In an article from 2016 it is supposed by interviews with operators of many big PV plants that 19% of the PV plants suffer from PID or PID suspicion [1]. This number represents an enormous economic loss for the plant operators and financial investors.

PID is a PV-failure mode that causes significant power reduction. Electrically, it can be described as a reduction of the shunt resistance of the affected cells. Laboratory investigations reveal that high negative electric potential differences between the cell and the grounded module frame (due to long module strings), high humidity and high temperature are the dominant root-causes for PID and its progression [2–5]. By this, ion transport from the glass into the cell is one proposed reason for PID [6]. The PID development is also discussed for some outdoor experiments [7–10].

The functionality of PV plants is usually controlled and inspected with the monitoring data retrieved from the inverter or by using imaging techniques such as infrared (IR)-thermography or electroluminescence imaging (EL) [11]. Whereas the monitoring data is collected continuously, but only on module string resolution, the imaging techniques take a lot more time to image the whole PV plant and evaluate the images on module level. Therefore, the imaging techniques have a much lower time resolution, but they help to localise the defective module and classify the defect type due to its spatial resolution down to cell level. However, the analysis of PV plants by imaging techniques is mainly of qualitative nature and algorithms to predict the power reduction from the images are still under research. Only simple correlations could be used if module substrings or whole modules are short- or open-circuited [12]. This is the reason why for a quantitative power reduction and degradation rate of PV plants *I*–*V* measurements or the monitoring data are commonly used [11, 13–16]. Typical analysis values include energy yield and performance ratio, with the latter more accurate as it includes the real irradiance [17]. In the case of PID, the correlation between thermography in field and module power reduction has been successfully shown [18–20]. Whereas Kaden *et al.* generated a reference curve correlating the temperature difference and power loss of the solar cells from experimental data, Buerhop *et al.* simply assumed no power generation for suspicious warmer cells. Both approaches led to good results. However, the question arises how good a prediction on the performance ratio and the degradation rate of a real PVplant by taking just a single IR-thermography inspection could actually be.

Fig. 1 *Image of the roof installation on a factory-varying installation angles, roof outlets, different orientation to the sun, soiling (visible on the module rows in the background of the picture), changes of shading situations due to various roof installations*

Therefore, for this paper, we investigated a 314kWp PV plant on an industrial rooftop in Portugal that revealed severe PID damage. Evaluation of the monitoring data of this PV plant was challenging due to partial shading of the modules by various roof installations (chimneys and other roof outlets) resulting in inhomogeneous irradiated modules within the module string by frequently alternating roof orientation and complexly connected strings (cf. Fig. 1). The annual energy yield for the last 3 years of operation was fluctuating and gave no indication for accelerated degradation of the PV plant. Nonetheless, we were able to show how the monitoring data of a real and complex PV installation can be evaluated so that degradation is detected even at this stage.

The use of aerial infrared (aIR) inspection has been used previously to identify PID-degraded modules [20–23]. In our case

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WILEY PROGRESS IN PHOTOVOLTAICS

RESEARCH ARTICLE

Evolution of cell cracks in PV-modules under field and laboratory conditions

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Abstract

Damaged modules, especially with cell cracks, can be observed quite often in photovoltaic-installations. Little knowledge exists about long-term stability of precracked modules at real operating conditions. Previous investigations and existing standards focus on the degradation of new, defect-free modules. This work highlights a twofold approach for life-time study of precracked modules: (1) outdoor exposure of 54 precracked modules for 1 year and (2) artificial stressing of 20 representative precracked modules with a novel load test setup simulating snow and wind loads. The outdoor exposure reveals that at moderate weather conditions, no changes were detectable, neither in electric performance nor in EL-images. However, the accelerated static load tests with stepwise increasing pressures point out that above a certain threshold, cracks grow. Below this threshold, formerly unseen cracks become visible at the loaded stage. In addition, modules with a smaller number of damaged cells have a stronger tendency to degrade further than modules with an already large number of cracked cells. Remarkably, the power output measured with a solar simulator after a stress test up to 2500 Pa (describing conservative proof conditions for severe snow loads according IEC 61215) remains unchanged for almost all modules.

KEYWORDS

cracks, electroluminescence, field test, mechanically loading, performance, pre-cracked modules

1 | INTRODUCTION

Operation and maintenance of photovoltaic (PV)-plants has gained importance during the last years to ensure a maximal energy production throughout the operating lifetime. Degradation and faults of all kinds negatively influence the reliability and lifetime of PV-installations. The analysis of the impact of these factors on technical and financial issues becomes more and more important for operators and investors. The presence of faults in combination with relevant degradation rates directly causes loss of power output and therefore a reduction of the return on investment.

Faults and defects caused by the manufacturing process, poor planning, or inadequate installation are often addressed in the technical press and workshops.[1] However, operational and environmental conditions can also damage or cause changes in PV-modules and other components of PV-plants.[2] This paper focuses on degradation and lifetime of cracked and fractured cells within PV-modules. To distinguish between cracks with and without impact on the electrically active cell area, the following formulations are used: cracked cell and fractured cell. A cracked cell shows just flaws, visible as lines, in EL-images. In a fractured cell, the crack affects the active cell area, visible as a darker area in the EL-image. In the latter case, it is assumed that the electrical connection between the cells parts separated by a crack is degraded, and the serial resistance increased.

Damage due to snow and wind loads are among the 5 most prominent damage reasons and amount to 10% to 30%[2-6] of failures. The failure mode ranges from cell fracture to complete module fracture with glass breakage. The most frequent module failure mode seems to be hot spots according to Jordan.[7] While glass breakage is easily visible, cell cracks and fractures demand special knowledge and equipment. The impact of these cell cracks on the long-term stability and how the cells degrade is not yet known.

Previous efforts concentrated on the degradation and aging of new modules. Standards describe test procedures, which focus on

Zellrisse – nur halb so schlimm

Feldstudie: Risse in den Solarzellen hat niemand gerne. Doch eine Studie zeigt, dass die Performance trotz großer Risse auch nach einigen starken Stürmen zumindest innerhalb eines Jahres nicht sinkt. Ein Autorenteam vom ZAE Bayern, der Allianz Risk Consulting, der Ecolution Engineers und von Adler Solar stellt das Ergebnis zur Diskussion.

Fotos: ZAE Bayern

Abbildung 1: Die Testanlage in Süddeutschland.

Photovoltaikmodule kranken häufig an Rissen und Brüchen, zum Beispiel nach der Herstellung, unsachgemäßem Transport, unsachgemäßer Montage, unsachgemäßer Betriebsführung, Umwelteinflüssen wie Schneelast, Hagelschlag oder Sturm, um an dieser Stelle nur einige der möglichen Ursachen zu nennen. Eine weit verbreitete Methode zur Visualisierung von Rissen in Solarzellen ist die Elektrolumineszenzmessung, auch EL-Messung abgekürzt. Sie ist prädestiniert, Rissstrukturen und „tote“, inaktive Zellflächen zwischen Rissen sichtbar zu machen. Neben der Durchführung der EL-Messungen im Labor, die die Demontage, das Handling und den Transport der zu untersuchenden Module erfordert, ist es heute mittels moderner Messtechnik möglich, EL-Aufnahmen auch problemlos und in großem Umfang an Modulen im Feld durchzuführen. Daher liegt es nahe, mit EL auch die Auswirkungen dieser Risse auf die Langzeitstabilität der Leistung von Photovoltaikmodulen zu untersuchen. Das ist bisher immer noch nicht geklärt.

Um diese Frage zu beantworten, haben wir uns zu einem einjährigen Langzeitversuch zusammengeschlossen. Mit der Auswertung kontinuierlich erfasster, zeitlich hochauflösender Monitoringdaten und punktueller EL-Aufnahmen sowie Modulleistungsmessungen wollten wir systematisch und detailliert untersuchen, ob im realen Betrieb kritische mechanische beziehungsweise thermomechanische Spannungen erreicht werden, die zu Risserzeugung und Risswachstum führen. Dabei sind Schnee- und Windlasten ebenso wie Temperaturunterschiede, beispielsweise Tag-Nacht-Zyklen oder Sommer-Winter-Zyklen, von zentraler Bedeutung für die Alterung, das heißt für die Rissentwicklung und deren Auswirkung auf die elektrische Performance installierter Photovoltaikmodule. Besonderes Interesse galt der Frage, ob stark rissbehaftete Module schneller und stärker in der Leistung degradieren als solche mit wenig rissbehafteten Zellen.

Das Wichtigste in Kürze

Ein Autorenteam hat mit Zellrissen behaftete Module ein Jahr lang in einer Outdooranlage untersucht.

Die Performance dieser Module war trotz Stürmen und Schnee nicht geringer als die einer Kontrollgruppe.

Die Elektrolumineszenzaufnahmen zeigen, dass nach einem Jahr weder die Anzahl der Zellrisse erhöht war noch ihre Ausprägung zugenommen hatte.

Die Autoren schließen daraus, dass vorhandene Zellrisse sich nicht notwendigerweise negativ auf das Degradationsverhalten auswirken und sie daher für den Betrieb weniger schlimm sind als landläufig angenommen. Ein signifikanter Einfluss auf die Stabilität der Module unter Realbedingungen konnte im Rahmen des Versuchs nicht festgestellt werden.

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Towards a full understanding of regioisomer effects of indene-C_{60} bisadduct acceptors in bulk heterojunction polymer solar cells†

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Indene-C_{60} bisadduct ($IC_{60}BA$), which can offer a significantly higher open-circuit voltage (V_{oc}) than monoadducts, has become the research focus as electron acceptor materials in polymer solar cells (PSCs) in recent years. However, despite its popularity, $IC_{60}BA$ have always been applied in PSCs as mixture of several regioisomers and the nature of this mixture has never been fully investigated and understood. Herein, for the first time, 12 major regioisomers of $IC_{60}BA$ were isolated and a full investigation was carried out with respect to their structure, abundance, solubility and their corresponding photovoltaic performance. The results show that the PSCs based on these regioisomeric structures present very diverse PCE and their photovoltaic performance was dramatically affected not only by the relative indene positions but also by the steric orientation of the two indene groups. Electrochemical studies further revealed that the effect of energetic disorder inside the $IC_{60}BA$ regioisomers on their photovoltaic performance is insignificant when applied in PSCs. However, the steric structures and solubility of the regioisomers were found to have significant impact on the morphology and bulk properties of the active layer of PSCs, which give rise to very different PCE of devices based on $IC_{60}BA$ regioisomers with different structures.

1. Introduction

Bulk heterojunction (BHJ) polymer solar cells (PSCs) have attracted tremendous scientific and industrial attention, owing to the advantages of having a simple device structure, being light weight and low cost and the possibility of being fabricated into flexible devices.[1–5] The photoactive layer of PSCs is commonly composed of blend film of electron-donating materials (donor) and electron-accepting materials (acceptor).[6]

Fullerene derivatives have been widely employed as an acceptor in PSCs because of their electron deficient character and semiconducting properties.[7,8] Great efforts have been made to develop high performance fullerene derivatives, such as [6,6]-phenyl-C_{61}-butyric acid methyl ester ($PC_{61}BM$) and others.[9–15] Because the electronic state of fullerenes can be tailored by addition of organic addends to the fullerene cage, one strategy for developing highly efficient fullerene acceptors is to increase the number of addends. This method can reduce the length of π-conjugation and increase the lowest unoccupied molecular orbital (LUMO) energy level as well as the open-circuit voltage (V_{oc}) of the PSCs with the fullerene derivative as an acceptor.[16] Indene-C_{60} bisadduct ($IC_{60}BA$) is the most representative fullerene bisadduct acceptor in PSCs. Promising PCEs over 7% have been reported for optimized PSCs with $IC_{60}BA$ as an acceptor.[17,18] However, although most solar cells based on fullerene bisadduct acceptors could present relatively high V_{oc},[19] only very few of them could deliver a PCE which is higher than the control devices based on PCBM. This can be partially ascribed to the unfavorable BHJ micro-morphology, leading to rather poor charge carrier dissociation efficiency and high recombination in the bulk.

Moreover, fullerene bisadducts, such as $IC_{60}BA$, are the mixture of several different regioisomers, which were directly applied together in PSCs without further isolation. Due to the different properties of each regioisomer,[12,20] much complicated molecular packing and energetic disorder are introduced to the BHJ structure by using the mixed regioisomers. Thus, the

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Exploring the Stability of Novel Wide Bandgap Perovskites by a Robot Based High Throughput Approach

Shi Chen, Yi Hou, Haiwei Chen, Xiaofeng Tang, Stefan Langner, Ning Li, Tobias Stubhan, Ievgen Levchuk, Ening Gu, Andres Osvet, and Christoph J. Brabec**

Currently, lead-based perovskites with mixed multiple cations and hybrid halides are attracting intense research interests due to their promising stability and high efficiency. A tremendous amount of 3D and 2D perovskite compositions and configurations are causing a strong demand for high throughput synthesis and characterization. Furthermore, wide bandgap (≈1.75 eV) perovskites as promising top-cell materials for perovskite–silicon tandem configurations require the screening of different compositions to overcome photoinduced halide segregation and still yielding a high open-circuit voltage (V_{oc}). Herein, a home-made high throughput robot setup is introduced performing automatic perovskite synthesis and characterization. Subsequently, four kinds of compositions (i.e., cation mixtures of Cs–methylammonium (MA), Cs– formamidinium (FA), MA–FA, and FA–MA) with an optical bandgap of ≈1.75 eV are identified as promising device candidates. For Cs–MA and Cs–FA films it is found that the Br–I phase segregation indeed can be overcome. Moreover, Cs–MA, MA–FA, and Cs–FA based devices exhibit an average V_{oc} of 1.17, 1.17, 1.12 V, and their maximum values approached 1.18, 1.19, 1.14 V, respectively, which are among the highest V_{oc} (≈1.2 V) values for ≈40% Br perovskite. These findings highlight that the high throughput approach can effectively and efficiently accelerate the invention of novel perovskites for advanced applications.

Hybrid organic–inorganic perovskites have emerged as highly efficient optoelectronic semiconductors and are being intensively investigated and developed for photovoltaic devices, detectors, light-emitting diodes, and laser architectures.[1–3] Hybrid organic–inorganic perovskites employ the general 3D perovskite formula ABX_3, where A is monovalent cation, such as $CH_3NH_3^+$ (MA^+), $HC(NH_2)_2^+$ (FA^+), Cs^+, or Rb^+, B represents metal cation (i.e., Pb^{2+}, Sn^{2+}), and X denotes the halide anion (i.e., I^-, Br^-, Cl^-). Currently, Pb-based perovskites with mixed multiple cations (binary, ternary, or quaternary) and hybrid halides (I/Br/Cl) are widely and intensively employed to overcome halide phase segregation, improve photostability and thermal stability, and achieve the highest efficiencies.[1,4] In addition, guanidinium (GA^+) or 5-aminovaleric acid cations (5-AVA^+) were also utilized to marginally substitute MA, FA, Cs, or Rb, providing more alternatives for mixed multiple cations in 3D perovskites.[5] These mixed multiple cations, in combination with hybrid halides, are able to output a tremendous amount of 3D perovskite configurations. Moreover, layered quasi-2D perovskites with the general formula $(RNH_3)_2(CH_3NH_3)_{n-1}Pb_nX_{3n+1}$ ($n = 1$, pure 2D layered; $n = \infty$, 3D structure; and n = defined integer; RNH_3 is a primary aliphatic or aromatic alkylammonium cation) have shown promising stability and efficiency.[6] A vast number of 2D perovskite configurations are created due to the larger space in cation selection and structure complexity. Being confronted with this large number of 3D and 2D perovskite configurations, the exploration and investigation of novel perovskites is creating a strong demand for a high throughput approach. High throughput synthesis and characterization will allow to accelerate the screening and identification of tens of thousands of novel and promising perovskite compositions in shortest time as required for advanced device engineering.

Suitable wide bandgap (≈1.75 V) perovskites have attracted great research attention due to the potential application of top-cell materials in the perovskite–silicon tandem configuration.[4,7,8] Perovskites with an organic cation (FA or MA) can achieve a bandgap of 1.7–1.8 eV via regulating the ratio of I and Br, however they undergo light-induced phase segregation in the mixed-halide system, where photoexcitation induces halide migration leading to lower bandgap iodide-rich domains and further limits the maximum obtainable V_{oc}.[9,10] Inorganic perovskites ($CsPbI_3$) with a bandgap of 1.73 eV have not been popular as compared to their hybrid counterparts due to the high-temperature synthesis process and inferior performance.[11]

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High-temperature thermographic phosphor mixture YAP/YAG:Dy^{3+} and its photoluminescence properties

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ABSTRACT

In this work we report on the investigation of high-temperature thermographic phosphors Dy^{3+}-doped yttrium aluminum garnet and the mixture of yttrium aluminum perovskite / yttrium aluminum garnet (YAP/YAG). The phosphors were synthesized by conventional high temperature solid-state method using lithium fluoride (LiF) as a flux. The latter serves also as a source of co-doping Li^+ and F^- ions affecting the luminescent properties. The photoluminescence intensity of YAP/YAG:Dy (75/25%) mixture was doubled at room temperature compared to YAG:Dy and the intensity ratio of the lines in the regions 450–460 and 480–500 nm was increased from 0.45 to 0.63 at 1293 K, favoring temperature measurements. Therefore, the mixture of $YAlO_3/Y_3Al_5O_{12}$:Dy is promising material for high temperature phosphor thermometry.

1. Introduction

Over the couple of decades there has been increasing need for advanced temperature measurement methods such as phosphor thermometry. Phosphor thermometry is based on the correlation between the photoluminescence (PL) properties of phosphors and temperature. Thermographic phosphors could be employed for temperature measurement in gas turbines [1,2] and engines [3] as well as for temperature analyses on gaseous flows [4–8]. This technique promises temperature detection of up to 1400 °C and more exhibiting low measurement errors. Phosphor thermometry may also be applied under very large background radiation as it utilizes active triggering of the luminescent signal via a light source such as a laser or LEDs. It was currently shown that signals buried in a 2000 time larger background signal may be easily detected with a rather simple dual-channel lock in setup and, accordingly, surface temperature may be deduced to at least up to 1000 K within an error of lower than 10 K [9]. Each application requests a material with certain optical and structural properties. In general, no phosphor fulfills the requirements for all applications. Thus, improvement of one or more properties is desirable in the quest for efficient thermographic phosphors [10,11], with high chemical stability, radiation hardness, high luminescent yield and in some cases short lifetime of PL [12,13]. Besides, phosphors should be inexpensive and easy to produce. Commonly used as host material in phosphor thermometry is the yttrium – aluminum Y_2O_3–Al_2O_3 system, which exists in three phases: yttrium aluminum monoclinic $Y_4Al_2O_9$ (YAM), yttrium aluminum perovskite $YAlO_3$ (YAP) and yttrium aluminum garnet $Y_3Al_5O_{12}$ (YAG). Generally, yttrium orthoaluminate YAlO3 (YAP) is a host material exhibiting good optical, thermal and mechanical properties similar to YAG. It is well-suited for the development of optical materials for different applications. Various rare earth dopants including Ce, Tb, Eu, Nd, Dy and also Cr and Bi have been incorporated into YAG and YAP to control the phosphor luminescence [14].

YAG doped with rare earth (RE^{3+}) ions [1], especially YAG:Dy [15,16], is one of the most widely used phosphors in phosphor thermometry [17]. The YAP crystals belong to a group of materials serving as host for laser crystals, scintillators, optical recording media and also as a substrate for thin films of high temperature superconductors [18]. Rare earth ion doped yttrium orthoaluminate ($YAlO_3$) phosphors are especially attractive for the development of optoelectronic devices [19,20]. $YAlO_3$:Eu^{3+} has been reported for successful storage and retrieval of 248-bit temporal optical data by accumulated photon echoes, owing to the long storage time of this material [21]. $YAlO_3$ phosphors co-activated with Eu^{3+} and Ce^{3+} have been widely applied in the development of flat panel field emission displays and plasma display [22]. Baig et al. reported thermoluminescence studies of $YAlO_3$:Dy^{3+} and its low stability to UV exposure compared to gamma irradiation [23]. Premkumar et al. suggested the possible application of

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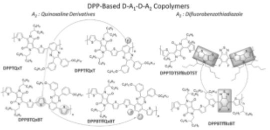
Beyond Donor–Acceptor (D–A) Approach: Structure–Optoelectronic Properties—Organic Photovoltaic Performance Correlation in New D–A_1–D–A_2 Low-Bandgap Conjugated Polymers

Christos L. Chochos,* Sofia Drakopoulou, Athanasios Katsouras, Benedetta M. Squeo, Christian Sprau, Alexander Colsmann, Vasilis G. Gregoriou, Alex-Palma Cando, Sybille Allard, Ullrich Scherf, Nicola Gasparini,* Negar Kazerouni, Tayebeh Ameri, Christoph J. Brabec, Apostolos Avgeropoulos*

Low-bandgap near-infrared polymers are usually synthesized using the common donor–acceptor (D–A) approach. However, recently polymer chemists are introducing more complex chemical concepts for better fine tuning of their optoelectronic properties. Usually these studies are limited to one or two polymer examples in each case study so far, though. In this study, the dependence of optoelectronic and macroscopic (device performance) properties in a series of six new D–A_1–D–A_2 low bandgap semiconducting polymers is reported for the first time. Correlation between the chemical structure of single-component polymer films and their optoelectronic properties has been achieved in terms of absorption maxima, optical bandgap, ionization potential, and electron affinity. Preliminary organic photovoltaic results based on blends of the D–A_1–D–A_2 polymers as the electron donor mixed with the fullerene derivative [6,6]-phenyl-C_{71}-butyric acid methyl ester demonstrate power conversion efficiencies close to 4% with short-circuit current densities (J_{sc}) of around 11 mA cm^{-2}, high fill factors up to 0.70, and high open-circuit voltages (V_{oc}s) of 0.70 V. All the devices are fabricated in an inverted architecture with the photoactive layer processed in air with doctor blade technique, showing the compatibility with roll-to-roll large-scale manufacturing processes.



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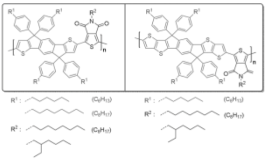
Rational Design of High-Performance Wide-Bandgap (≈2 eV) Polymer Semiconductors as Electron Donors in Organic Photovoltaics Exhibiting High Open Circuit Voltages (≈1 V)

Christos L. Chochos,* Athanasios Katsouras, Nicola Gasparini, Chrysanthos Koulogiannis, Tayebeh Ameri, Christoph J. Brabec, Apostolos Avgeropoulos

Systematic optimization of the chemical structure of wide-bandgap (≈2.0 eV) "donor–acceptor" copolymers consisting of indacenodithiophene or indacenodithieno[3,2-*b*]thiophene as the electron-rich unit and thieno[3,4-*c*]pyrrole-4,6-dione as the electron-deficient moiety in terms of alkyl side chain engineering and distance of the electron-rich and electron-deficient monomers within the repeat unit of the polymer chain results in high-performance electron donor materials for organic photovoltaics. Specifically, preliminary results demonstrate extremely high open circuit voltages (V_{oc}s) of ≈1.0 V, reasonable short circuit current density (J_{sc}) of around 11 mA cm^{-2}, and moderate fill factors resulting in efficiencies close to 6%. All the devices are fabricated in an inverted architecture with the photoactive layer processed by doctor blade equipment, showing the compatibility with roll-to-roll large-scale manufacturing processes. From the correlation of the chemical structure—optoelectronic properties—photovoltaic performance, a rational guide toward further optimization of the chemical structure in this family of copolymers, has been achieved.



1. Introduction

The certified power conversion efficiencies (PCEs) of polymer-fullerene bulk heterojunction solar cells[1] are now above 10% in single-junction binary OPVs (consisting of one donor material and one acceptor material).[2] This recent improvement in device performance is due to the design and synthesis of new donor–acceptor (D–A) polymers exhibiting energy levels and band gaps optimized for high PCE.[3] However, in order to further increase the PCEs in OPVs a very effective strategy for overcoming the limitations of binary blend OPVs is the use of tandem or ternary architecture.[4,5] Therefore, the potential of many

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The role of chemical structure in indacenodithienothiophene-*alt*-benzothiadiazole copolymers for high performance organic solar cells with improved photo-stability through minimization of burn-in loss†

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It is of upmost importance to gain an in-depth understanding of the role of the polymer chemical structure in the performance of the corresponding organic solar cell (OSC) and its degradation behavior, which is currently insufficiently explored. Achieving these correlations will set new design rules towards further optimization of polymer chemical structures for OSCs exhibiting high performances and long stability. In this study, our efforts have been focused on identifying how the nature of aryl substituents and the number of fluorine atoms anchored in the backbone of indacenodithieno[3,2-*b*]thiophene (IDTT) based polymers influence their optoelectronic properties, the OSC performances and their degradation mechanisms. The most important outcome of this study is the demonstration that standard initial burn-in loss is primary attributed to microstructure instabilities. Furthermore, the initial burn-in loss could be substantially reduced through the rational design of the polymeric semiconductor's chemical structure, leading to improved lifetimes and low (20%) initial power conversion efficiency loss. In particular, we identify the beneficial effect of the presence of the two fluorine atoms on the benzo[c][1,2,5]thiadiazole (BTD), as compared to the non-fluorinated and mono-fluorinated analogues, in decreasing the burn-in by reducing the microstructure instabilities regardless of the aryl substituent that is present in the polymer backbone.

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1. Introduction

It is becoming increasingly clear that systematic optimization of the chemical structure of "donor–acceptor" (D–A) polymeric semiconductors as electron donors in organic photovoltaics (OPVs) is a challenging task for which accurate guidelines are yet to be determined.[1] Several different structural and molecular parameters are crucial ingredients for obtaining polymeric semiconductors that simultaneously possess high power conversion efficiencies (PCEs), easy processability in common organic solvents and enhanced stability in OPVs. Although the PCE of OPV devices has been considerably improved to over 12%,[2] their stability (or lifetime) is still too poor to consider the aspect of large commercialization.[3]

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† Electronic supplementary information (ESI) available: Synthesis, gel permeation chromatography, absorption spectroscopy and cyclic voltammetry characterisation of the polymers. Fabrication and characterisation of organic solar cells, transport characteristics and transient absorption spectroscopy of the devices. High resolution transmission electron microscopy and micro-Raman spectroscopy. See DOI: 10.1039/c7ta09224e

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Suppression of Thermally Induced Fullerene Aggregation in Polyfullerene-Based Multiacceptor Organic Solar Cells

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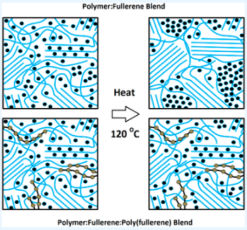
Supporting Information

ABSTRACT: A novel main-chain polyfullerene, poly[fullerene-*alt*-2,5-bis(octyloxy)-terephthalaldehyde] (PPC4), is investigated for its hypothesized superior morphological stability as an electron-accepting material in organic photovoltaics relative to the widely used fullerene phenyl-C61-butyric acid methyl ester (PCBM). When mixed with poly(3-hexylthiophene-2,5-diyl) (P3HT), PPC4 affords low-charge-generation yields because of poor intermixing within the blend. The adoption of a multiacceptor system, by introducing PCBM into the P3HT:polyfullerene blend, was found to lead to a 3-fold enhancement in charge generation, affording power conversion efficiencies very close to that of the prototypical P3HT:PCBM binary control. Upon thermal stressing and in contrast to the P3HT:PCBM binary, photovoltaic devices based on the multiacceptor system demonstrated significantly improved stability, outperforming the control because of suppression of the PCBM migration and aggregation processes responsible for rapid device failure. We rationalize the influence of the fullerene miscibility and its implications on the device performance in terms of a thermodynamic model based on Flory−Huggins solution theory. Finally, the potential universal applicability of this approach for thermal stabilization of organic solar cells is demonstrated, utilizing an alternative low-band-gap polymer-donor system.



KEYWORDS: *organic photovoltaics, main-chain polyfullerenes, thermal stability, multi acceptor composite blend, fullerene aggregation*

INTRODUCTION

Organic photovoltaics (OPV) continues to attract significant interest as a promising, commercially viable technology because of their potential for large-scale, low-cost production of low-weight and flexible modules.[1,2] While perovskite-based cells might be seen as formidable competitors,[3] there is an expectation of complementarity between these two systems, given that OPV can be more acceptably installed on buildings and in appliances because of its nontoxic nature. In the commercial sphere, OPV has witnessed a dramatic increase in its employment as building-integrated photovoltaics around the world, underscoring its potential beyond niche markets.[4] As the technology emerges from adolescence, it becomes even more important to address the current hindrances to its further progress. Factors, such as its device and module efficiency as well as processability, have developed substantially in recent years, with many systems achieving power conversion efficiencies (PCEs) of over 10% and 5%, respectively.[5−8] However, as OPV becomes more competitive with respect to the more established technologies such as CIGS and a-Si (21.0% and 10.2% laboratory-scale efficiencies respectively),[7] it is important for the research community to continue to build an understanding of and resolve the fundamental challenges with respect to long-term device stability, addressing reagents and mechanisms responsible for device failure. Much work has been conducted in this regard, identifying and elucidating the influence of the key drivers of device degradation, namely, oxygen, water, heat, and light.[9−14] Further advances are

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Crystallization of Sensitizers Controls Morphology and Performance in Si-/C-PCPDTBT-Sensitized P3HT:ICBA Ternary Blends

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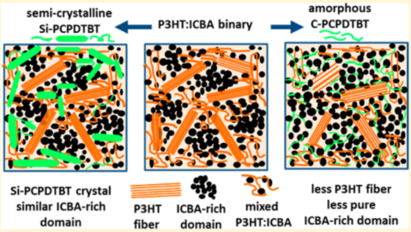
Supporting Information



ABSTRACT: Organic solar cells based on multinary components are promising to further boost the device performance. The complex interplay of the morphology and functionality needs further investigations. Here, we report on a systematic study on the morphology evolution of prototype ternary systems upon adding sensitizers featuring similar chemical structures but dramatically different crystallinity, namely poly(3-hexylthiophene) (P3HT) and indene-C_{60}-bis-adduct (ICBA) blends with poly[(4,4′-bis(2-ethylhexyl)-dithieno[3,2-*b*:2′,3′-*d*]silole)-2,6-diyl-*alt*-(4,7-bis(2-thienyl)-2,1,3-benzothiadi-azole)-5,5′-diyl] (Si-PCPDTBT) and poly-[2,6-(4,4-bis(2-ethylhexyl)-4*H*-cyclopenta[2,1-*b*;3,4-*b*′]-dithiophene)-*alt*-4,7-(2,1,3-benzothiadiazole)] (C-PCPDTBT), employing energy-filtered transmission electron microscopy (EFTEM) and resonant soft X-ray scattering (RSoXS). In addition, a combined density functional theory (DFT) and artificial neuronal network (ANN) computational approach has been utilized to calculate the solubility parameters and Flory−Huggins intermolecular parameters to evaluate the influence of miscibility on the final morphology. Our experiments reveal that the domain spacing and purity of ICBA-rich domains are retained in Si-PCPDTBT-based systems but are strongly reduced in C-PCPDTBT-based ternary systems. The P3HT fiber structure are retained at low sensitizer content but dramatically reduced at high sensitizer content. The theoretical calculations reveal very similar miscibility/compatibility between the two sensitizers and ICBA as well as P3HT. Thus, we conclude that mainly the crystallization of Si-PCPDTBT drives the nanostructure evolution in the ternary systems, while this driving force is absent in C-PCPDTBT-based ternary blends.

INTRODUCTION

Organic solar cells (OSCs) have improved considerably in power conversion efficiency (PCE) over the past two decades owing to the effort of new material development, advanced device engineering, and further understanding of device working mechanism.[1−6] The most intensively studied polymer:-fullerene binary single junction devices based on newly developed polymers still face the problem of having a narrow absorption range over the whole solar spectrum. To increase the absorption range, tandem and/or ternary solar cells are considered to be the most promising strategies. Tandem solar cells have achieved great success by device engineering and materials development.[7−12] Although ternary solar cells are much more promising in terms of device fabrication, there are still only a few successful cases.[13−22] Understanding the mechanism of success/failure of ternary solar cells is critical for further optimization of such devices. Charge generation and transport are much more complex in ternary solar cells than in binary systems. So far, several models have been proposed for the ternary solar cells, namely charge transfer,[16−19] energy transfer,[20,21] alloy formation,[22] and two CT states or parallel like model,[23] which are very system dependent. In all cases, the morphology change upon adding a third component in the host matrix must be well investigated in order to fully understand the working mechanism.

In previous publications,[16−18] the low band gap hetero-analogues poly[(4,4′-bis(2-ethylhexyl)dithieno[3,2-*b*:2′,3′-*d*]-silole)-2,6-diyl-*alt*-(4,7-bis(2-thienyl)-2,1,3-benzothiadi-azole)-5,5′-diyl] (Si-PCPDTBT)[24] and poly[2,6-(4,4-bis(2-ethyl-hexyl)-4*H*-cyclopenta[2,1-*b*;3,4-*b*′]-dithiophene)-*alt*-4,7-(2,1,3-

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Overcoming Interfacial Losses in Solution-Processed Organic Multi-Junction Solar Cells

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Organic solar cells are promising in terms of full-solution-processing which enables low-cost and large-scale fabrication. While single-junction solar cells have seen a boost in power conversion efficiency (PCE), multi-junction solar cells are promising to further enhance the PCE. In all-solution-processed multi-junction solar cells, interfacial losses are often encountered between hole-transporting layer (HTL) and the active layers and therefore greatly limit the application of newly developed high-performance donor and acceptor materials in multi-junction solar cells. Here, the authors report on a systematic study of interface losses in both single-junction and multi-junction solar cells based on representative polymer donors and HTLs using electron spectroscopy and time-of-flight secondary ion mass spectrometry. It is found that a facile mixed HTL containing poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) and MoO_x nanoparticles successfully overcomes the interfacial losses in both single- and multi-junction solar cells based on various active layers by reducing interface protonation, promoting better energy-level alignment, and forming a dense and smooth layer. Solution-processed single-junction solar cells are demonstrated to reach the same performance as with evaporated MoO_x (over 7%). Multi-junction solar cells with polymers containing nitrogen atoms as the first layer and the mixed PEDOT:PSS and MoO_x nanoparticles as hole extraction layer reach fill factor (FF) of over 60%, and PCE of over 8%, while the identical stack with pristine PEDOT:PSS or MoO_x nanoparticles show FF smaller than 50% and PCE less than 5%.

1. Introduction

Organic photovoltaics (OPVs) have gained extensive research attention in the last two decades due to their compatibility with low-cost and large-scale production techniques, such as roll-to-roll processing.[1–4] The power conversion efficiency (PCE) of OPV devices has seen a boost in the last ten years due to new material developments, device engineering and further understanding of the device mechanisms.[5–13] State-of-the-art single-junction solar cells with PCE larger than 10% have been reported by many groups.[6,11] However, considering the relatively narrow absorption windows of organic materials compared to their inorganic counterparts, multi-junction solar cells are promising to further boost the overall performance by utilization of more photons.[14–19] A maximum PCE of 21% is theoretically predicted for organic double-junction solar cells.[3]

The heart of organic multi-junction solar cells is an efficient solution-processed intermediate layer (IML), which generally consists of a hole-transporting

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High-performance ternary organic solar cells with thick active layer exceeding 11% efficiency†

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We present a novel ternary organic solar cell with an uncommonly thick active layer (~300 nm), featuring thickness invariant charge carrier recombination and delivering 11% power conversion efficiency (PCE). A ternary blend was used to demonstrate photovoltaic modules of high technological relevance both on glass and flexible substrates, yielding 8.2% and 6.8% PCE, respectively.

Broader context

One key advantage of solution-processable organic semiconductors is the opportunity of blending different materials in order to attain novel material properties and applications. The concept of ternary blend organic solar cells makes use of exactly that idea: three (or more) organic chromphores are combined to better match the solar irradiance spectrum and thus increase the amount of light absorbed, which, in turn, will increase the power output of the solar cell. However, the charge transport limitations of many current generation polymer blends typically require rather low active layer thicknesses (around 100 nm) for optimum performance. Here, in addition to extending the absorption window of organic solar cells by adding a near infrared polymer, we demonstrate devices with unusually thick active layers (~300 nm) and power conversion efficiencies beyond 11%. Motivated by the possibility to process thick-film devices based on ternary blends, we demonstrate solar modules consisting of three solar cells connected is series, delivering 8.2% and 6.8% power conversion efficiency on glass and flexible substrates, respectively. These results underscore the relevance of ternary photovoltaic polymer blends for future upscaling technologies.

The concept of organic bulk-heterojunction (BHJ) ternary solar cells has attracted increased interest in recent years for its capability to not only extend the spectral absorption range but also manipulate the recombination behavior of binary polymer: fullerene devices.[1–8] Typically consisting of two polymers (or small molecules) with complementary absorption spectra and one acceptor (or one donor and two acceptors), ternary blends surpassed the important 10% power conversion efficiency (PCE) threshold towards industrial application while maintaining the same level of simplicity for processing a single junction architecture.[4] The addition of a third absorber/chromophore is thus likely to contribute to a shorter energy payback time.[9]

Lately, a wide range of materials have been adopted to function as ternary sensitizers, such as polymers,[8,10–13] small molecules,[14] quantum dots[15] and dyes.[16,17] However, the charge transport limitations of many current generation polymer blends typically require rather low active layer thicknesses (around 100 nm) for optimum performance, limiting the internal quantum efficiency of thick active layers with more practical relevance (beyond 200 nm). The reasons for the low performance are multiple. It could be associated with low charge carrier mobility because of reduced crystallinity.[18,19] In this case, the low purity of domains may translate into increased charge carrier recombination, leading to mainly poor fill factors (FF). A critical aspect affecting charge transport and the performance in general is the sensitive morphology of the active layer, which could have detrimental implications in the case of thick layers because of compositional gradients or strong variations in structural orientation.[18,19] Recently, important progress in PCEs has been achieved in the case of binary donor–acceptor thick film heterojunctions mainly due to the extensive research effort towards understanding and controlling the morphology of BHJ blends as well as the development of organic semiconductors with much improved charge transport capabilities.[19–21] While adding a third component to the bulk heterojunction may increase the spectral sensitivity of organic solar cell devices, it is apparent that it may also add complexity, making it difficult to uphold a morphology that maintains efficient transport, particularly

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Polymer:Nonfullerene Bulk Heterojunction Solar Cells with Exceptionally Low Recombination Rates

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Organic semiconductors are in general known to have an inherently lower charge carrier mobility compared to their inorganic counterparts. Bimolecular recombination of holes and electrons is an important loss mechanism and can often be described by the Langevin recombination model. Here, the device physics of bulk heterojunction solar cells based on a nonfullerene acceptor (IDTBR) in combination with poly(3-hexylthiophene) (P3HT) are elucidated, showing an unprecedentedly low bimolecular recombination rate. The high fill factor observed (above 65%) is attributed to non-Langevin behavior with a Langevin prefactor (β/β_L) of 1.9×10^{-4}. The absence of parasitic recombination and high charge carrier lifetimes in P3HT:IDTBR solar cells inform an almost ideal bimolecular recombination behavior. This exceptional recombination behavior is explored to fabricate devices with layer thicknesses up to 450 nm without significant performance losses. The determination of the photoexcited carrier mobility by time-of-flight measurements reveals a long-lived and nonthermalized carrier transport as the origin for the exceptional transport physics. The crystalline microstructure arrangement of both components is suggested to be decisive for this slow recombination dynamics. Further, the thickness-independent power conversion efficiency is of utmost technological relevance for upscaling production and reiterates the importance of understanding material design in the context of low bimolecular recombination.

Solution processed organic polymer photovoltaics are a promising technology for delivering light to energy conversion in a sustainable fashion.[1] With devices now consistently surpassing the commercially important 10% barrier, organic photovoltaics (OPV) are on the verge of becoming cost competitive with earlier generation photovoltaics.[2–4] This was feasible because of successful attempts to overcome intrinsic limitations related to the narrow spectral absorption and the low charge carrier mobility of the donor materials used in the bulk heterojunction.[5,6] However, many high performance polymers are still considered cost prohibitive (several $k per gram at lab scale) because they consist of complex building blocks that are carefully tethered together in a sequence of multiple reaction steps and require laborious purification measures. Conversely, the prototypical polymer poly(3-hexylthiophene) (P3HT) was long considered as one of the best suited candidates for enabling a viable transition of this technology from the lab to large active areas (potentially few tens of $ per gram),[7,8] not only for its simple chemical structure and straightforward synthesis route but also for the possibility to be processed with thicknesses >200 nm, which is vital for large area processing. The realization of thick active layers is related to a balanced hole and electron mobility and low charge carrier recombination, consistent with non-Langevin behavior.[9,10] Unfortunately, the rather low power conversion efficiency (PCE) of P3HT:[6,6]-phenyl-C61-butyric acid methyl ester (PCBM)-based devices,

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Burn-in Free Nonfullerene-Based Organic Solar Cells

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Organic solar cells that are free of burn-in, the commonly observed rapid performance loss under light, are presented. The solar cells are based on poly(3-hexylthiophene) (P3HT) with varying molecular weights and a non-fullerene acceptor (rhodanine-benzothiadiazole-coupled indacenodithiophene, IDTBR) and are fabricated in air. P3HT:IDTBR solar cells light-soaked over the course of 2000 h lose about 5% of power conversion efficiency (PCE), in stark contrast to [6,6]-Phenyl C61 butyric acid methyl ester (PCBM)-based solar cells whose PCE shows a burn-in that extends over several hundreds of hours and levels off at a loss of ≈34%. Replacing PCBM with IDTBR prevents short-circuit current losses due to fullerene dimerization and inhibits disorder-induced open-circuit voltage losses, indicating a very robust device operation that is insensitive to defect states. Small losses in fill factor over time are proposed to originate from polymer or interface defects. Finally, the combination of enhanced efficiency and stability in P3HT:IDTBR increases the lifetime energy yield by more than a factor of 10 when compared with the same type of devices using a fullerene-based acceptor instead.

With many groups now consistently reporting single junction organic solar cells with power conversion efficiencies well above the psychologically important 10% threshold, this technology is becoming increasingly competitive with other thin-film photovoltaic technologies.[1,2] On the downside, the device longevity remains a critical problem and attention needs to be directed toward understanding and solving the current lifetime limitations. It is well established that environmental factors such as oxygen and water in the presence of light can lead to irreversible performance breakdown mostly due to photo-oxidation of the active layer and corrosion of the metal electrode.[3,4] However, even in the absence of these extrinsic factors, i.e., in the case of firmly packaged devices, short- and long-term photovoltaic performance loss is still observed under operation.[5,6] A particularly severe phenomenon is the so-called light-induced or temperature-induced burn-in—a term that originates from common practice in semiconductor devices referring to the application of electrical or temperature stress in order to detect or mitigate early failures.[7] In organic polymer based solar cells, the burn-in period reflects an early, near to exponential photovoltaic performance roll-off.[8] The effect may deplete the initial power conversion efficiency (PCE) by as much as 20%–60%,[9] depending on the material system. It typically occurs so rapidly that it is generally accepted to specify the lifetime of the device post burn-in phase, i.e., neglecting the early loss in performance.[10] This intrinsic, light-driven degradation observation is thought to be mostly determined by material properties of the active layer and less due to interfaces and electrodes.[9,10] For instance, light-induced burn-in has been experimentally and theoretically correlated, although to different extent, with photochemical reactions,[11] critical concentrations of chemical and metal impurities,[12,13] molecular weight distribution,[14] degree of crystallinity,[15] cross-linking,[16] processing additives,[17] and the formation of long-lived radicals.[18] In light of these considerations, current state of the art envisions photovoltaic materials with elevated levels of photostability and high degree of purity and crystallinity, ideally free of radical-forming processing additives. It thus appears forthcoming to consider conjugated polymers of low structural complexity and relatively inert functional building blocks that tend to adopt a very ordered microstructure in thin films. The prototypical homopolymer poly(3-hexylthiophene) (P3HT) combines those characteristics. Yet, when blended with common [6,6]-Phenyl C61 butyric acid methyl ester (PCBM) fullerene acceptor, P3HT, in addition to the rather low power conversion efficiency, may feature a significant burn-in loss, primarily in

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Indacenodithienothiophene-Based Ternary Organic Solar Cells

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One of the key aspects to achieve high efficiency in ternary bulk-hetorojunction solar cells is the physical and chemical compatibility between the donor materials. Here, we report the synthesis of a novel conjugated polymer (P1) containing alternating pyridyl[2,1,3]thiadiazole between two different donor fragments, dithienosilole and indacenodithienothiophene (IDTT), used as a sensitizer in a host system of indacenodithieno[3,2-b]thiophene,2,3-bis(3-(octyloxy)phenyl)quinoxaline (PIDTTQ) and [6,6]-phenyl C_{70} butyric acid methyl ester ($PC_{71}BM$). We found that the use of the same IDTT unit in the host and guest materials does not lead to significant changes in the morphology of the ternary blend compared to the host binary. With the complementary use of optoelectronic characterizations, we found that the ternary cells suffer from a lower mobility-lifetime (μτ) product, adversely impacting the fill factor. However, the significant light harvesting in the near infrared region improvement, compensating the transport losses, results in an overall power conversion efficiency enhancement of ~7% for ternary blends as compared to the $PIDTTQ:PC_{71}BM$ devices.

Keywords: organic solar cells, ternary devices, OPV, IDTT, organic electronics

INTRODUCTION

During the last decades, the power conversion efficiency (PCE) of organic bulk-hetorojunction (BHJ) solar cells based on donor/acceptor blends surpassed the 10% threshold, mainly due to the discovery of novel materials as well as device structure engineering (Liu et al., 2014; He et al., 2015; Holliday et al., 2016; Huang et al., 2016; Spyropoulos et al., 2016; Zhao et al., 2016). Polymers and/or small molecules, used as donor materials, in combination with fullerene derivatives, used as acceptor, are the common active components in BHJ devices (Zhang et al., 2014; Lu et al., 2015c; Min et al., 2015; Squeo et al., 2015). Due to the narrow absorption of the donor materials, one of the main challenges in order to further boost the PCE of organic solar cells is to achieve better absorption match to the solar irradiance spectrum. In this regard, two main concepts have been developed: tandem and ternary organic solar cells (Ameri et al., 2009, 2013a,b; Li et al., 2013; You et al., 2013; Spyropoulos et al., 2014; Lu et al., 2015b; Yang et al., 2015; Cheng et al., 2016; Goh et al., 2016;

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Polyaromatics

Acenequinocumulenes: Lateral and Vertical π-Extended Analogues of Tetracyanoquinodimethane (TCNQ)

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Abstract: We have designed a series of molecules and developed synthetic methodology that allows for the inclusion of structural diversity along both the lateral and vertical axes of the basic **TCNQ** skeleton. In the lateral direction, benzoannulation extends the π-system through (hetero)acene formation, whereas incorporation of a [3]cumulene increases delocalization vertically. The potential of these new molecules as semiconductors is explored through UV/Vis spectroscopy, cyclic voltammetry, X-ray crystallography, thin-film formation, and mobility measurements (using space charge limited current measurements).

Introduction

The past few decades have seen spectacular achievements in the development of organic semiconductors in terms of stability, processability, and charge carrier mobility.[1,2] This progress highlights the beauty of synthetic organic chemistry, which offers the tools to design, explore, and tune the properties of molecules for use in devices such as organic sensors,[3,4] field-effect transistors (OFETs),[4–6] organic light-emitting diodes (OLEDs),[7–9] and organic photovoltaics (OPVs).[10–13] Organic semiconductors are often classified into two categories, p-type (donor, hole conducting) and n-type (acceptor, electron conducting). In the case of p-type organic semiconductors, many requisite properties have been fulfilled,[1,2,6,14,15] whereas the realization of n-type organic materials remains troubled by issues such as complex synthesis, instability in air, poor solubility, large electron-injection barriers, and low charge carrier mobilities.[16–19]

One of the most common non-fullerene compound classes used as n-type semiconductors are cyano-based acceptors such as tetracyanoethylene (**TCNE**, Figure 1)[20–23] and the more stable, π-extended analogue tetracyanoquinodimethane (**TCNQ**).[24] First reported in 1960 by Acker et al.,[25,26] pristine **TCNQ** has become one of the most extensively studied acceptor materials.[26–29] The electron accepting abilities of **TCNQ** have been further fine-tuned through substitution,[24,30–32] incorporation of heteroatoms,[24,32–34] and, most commonly, extension of the π-system by lateral benzoannulation to give π–extended **TCNQ** derivatives (**exTCNQs**).[24,32,35–38] It was originally expected that **exTCNQs** could offer more stable and improved conducting materials.[37,39] In reality, however, the π-expansion does not necessarily result in enhanced acceptor properties, and derivatives such as **TCAQ**, **TCTQ**, and **TCPQ**[24,32,36–38] show non-planar structures that give rise to the so-called "butterfly" conformation and can hinder π-communication and effective charge transport.[40,41] Despite lower electron-accepting properties, **exTCNQs** have been remarkably adapted through structural modification.[42] For example, **TCTQ** and **BDCNBA** undergo photoinduced electron transfer (PET) almost as efficiently as fullerene C_{60},[43,44] while **TCAQ** derivatives have demonstrated effectiveness in a range of PET processes.[45–49] These results are significant, since they emphasize that device efficiency is not solely dictated by acceptor strength, and that shape and/or solid-state packing of the material are also crucial parameters.[50]

To date, there are few **exTCNQ** derivatives that exceed the length of **TCTQ**,[37,50–53] and most derive from the pioneering work of Martin and Hanack, including **5,14-TCPQ** and **6,13-TCPQ**,[37,51] and Yamada et al. who reported **TBPQ**.[52] In these cases, however, the poor solubility in common organic solvents restricts practical use, and large HOMO–LUMO gaps limit visible absorptions.[51,52]

We became fascinated by the question of whether lateral and vertical substitution of **exTCNQ** derivatives could be used to augment desirable properties. We hypothesized that a [3]cumulene spacer at the "tail" position could be used to provide

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INVITED REVIEW

This section of Journal of Materials Research is reserved for papers that are reviews of literature in a given area.

In situ characterization methods for evaluating microstructure formation and drying kinetics of solution-processed organic bulk-heterojunction films

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Recently, *in situ* characterization methods have attracted increasing attention, especially in organic photovoltaics (OPV) field, since they provide greater insight into the mechanism of film formation, thus help to identify optimized processing conditions used to process the most efficient organic bulk-heterojunction thin films. In combination with various powerful X-ray-based characterization methods, several studies observed the morphological changes under the influence of different processing conditions. In this review, we summarize the fundamentals and implementation of X-ray-based and optical characterization methods, utilized in *in situ* mode and introduce the reader a better overview of the information acquired from a given technique in terms of microstructure formation in OPV. While we give a chronological development of *in situ* characterization methods in the field of OPV, we discuss the interplay between thermodynamics of solutions and drying kinetics of different types of organic blends.

I. INTRODUCTION

Organic solar cells are the solar cells based on organic semiconductors as photo-active materials, such as polymers, small molecules, and fullerenes. Since 2000, together with the Nobel Prize in Chemistry awarded jointly to Alan J. Heeger, Alan G. MacDiarmid, and Hideki Shirakawa for the discovery and development of conductive polymers, the field of organic photovoltaics (OPV) has seen an unprecedented growth of interest. Especially the advantages of up-scaling, low cost, light weight, flexibility and solution processability have escalated the research on OPV within the last decade.[1–5]

Organic electronic materials are conjugated solids at which the absorption and charge transport are determined by the partially delocalized π and π^* orbitals. The photoactive layer of an organic solar cell consists of a donor and an acceptor material.[3] Photons absorbed by the donor material lead to electron–hole pairs (i.e., Frenkel excitons), which do not spontaneously dissociate into free charge carriers because of the low dielectric constants of these materials. Hence, a strong driving force (i.e., a local electrical field) is needed to dissociate excitons into free charge carriers, which is generally achieved by interfacial electric field originating from the differences in electron affinity and ionization potential between donor and acceptor materials.[6,7] Due to the short excitons diffusion lengths (1–10 nm), exciton diffusion has become one of the biggest limiting steps for photocarrier generation. This encouraged scientists to develop an alternative structure for the photoactive layer, so called, bulk-heterojunction (BHJ).[8,9]

An optimized BHJ is a finely mixed, yet phase separated network (Fig. 1), which ensures the length scales for efficient exciton dissociation and percolated pathways of donor and acceptor for the most efficient charge carrier transport to the respective electrodes.[10] Two commonly used deposition methods for fabrication of BHJ solar cells are thermal evaporation and solution processing. The power conversion efficiency (PCE) of BHJ solar cells has been rapidly reached up to 13.2% by design of novel materials, device architectures, and precise device optimization. By 2016, Heliatek reported

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ORIGINAL ARTICLE

The fabrication of color-tunable organic light-emitting diode displays via solution processing

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Electroluminescent devices based on organic semiconductors have attracted significant attention owing to their promising applications in flat-panel displays. The conventional display pixel consisting of side-by-side arrayed red, green and blue subpixels represents the mature technology but bears an intrinsic deficiency of a low pixel density. Constructing an individual color-tunable pixel that comprises vertically stacked subpixels is considered an advanced technology. Although color-tunable organic light-emitting diodes (OLEDs) have been fabricated using the vacuum deposition of small molecules, the solution processing of conjugated polymers would enable a much simpler and inexpensive manufacturing process. Here we present the all-solution processing of color-tunable OLEDs comprising two vertically stacked polymer emitters. A thin layer of highly conducting and transparent silver nanowires is introduced as the intermediate charge injection contact, which allows the emission spectrum and intensity of the tandem devices to be seamlessly manipulated. To demonstrate a viable application of this technology, a 4-by-4 pixelated matrix color-tunable display was fabricated.

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Keywords: color tunable; oLED display; organic light-emitting diode; silver nanowires; solution processing; tandem

INTRODUCTION

Organic light-emitting diodes (OLEDs) based on small organic molecules or conjugated polymers exhibit unique features of high brittleness, a low turn-on voltage and a wide range of colors[1–3]. In combination with their solution-processing compatibility, these favorable characteristics make OLED devices potential candidates for use in the manufacture of low-cost full-color displays[4–6]. Recently, thermally deposited OLEDs made of small molecules have found market applications in consumer electronic devices such as Samsung's and LG's flat-panel TVs and the Apple watch. Currently, the most successful full-color flat-panel display technology is based on a 'side-by-side' geometry, where the individual emitting pixel consists of three laterally arrayed red (R), green (G) and blue (B) subpixels[5–7]. However, a major drawback of this 'side-by-side' geometry is the inherently restricted resolution caused by the low geometric fill factor.

It is known that many organic light-emitting materials exhibit large Franck–Condon red shifts between their absorption and emission spectra[8–10]. A high electroluminescence performance can be achieved by using very thin films. These unique properties enable the fabrication of visibly semitransparent OLED devices[11,12]. The semitransparency of these organic thin films permits the manufacture of vertically stacked pixels by sequentially depositing two or more subdiodes on top of each other. Color-tunable emitting pixels can be realized by such a vertically stacked approach. Compared to the conventional side-by-side geometry, the vertically stacked architecture offers the advantages of easier device manufacture and a smaller pixel size and, thus, a higher fill factor[13].

The essential task for the fabrication of vertically stacked color-tunable OLED devices is to deposit a thin layer of a transparent conducting film as a common charge injection contact for the subdiodes. In the 1990s, Forrest and co-authors[14,15] first conceived and fabricated color-tunable OLED devices by monolithically depositing small molecular diodes that were interconnected with thermally deposited metal alloys. Following these pioneering works, several groups fabricated color-tunable OLED cells via the vacuum deposition of small molecular emitting materials and analogous interconnection layers consisting of thin metal films (for example, Au and Ag)[16–19]. However, all of the emitting materials and the intermediate layers in these devices were deposited via a high-vacuum process, which increased the complexity of the device fabrication. Moreover, the intermediate electrode made of thin metal films can absorb a significant amount of emitted light and introduce unwanted microcavity effects[15,20]. In contrast, the use of a solution process for the conjugated polymer emitters and the interface materials can result in a much simpler and less expensive fabrication process. Nevertheless, due to the challenge of introducing a highly transparent and conducting contact layer that can be solution-deposited between subdiodes, the

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Technical Note

Contactless temperature determination using dual-channel lock-in phosphor thermometry

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Abstract

In this paper, we present dual-channel lock-in phosphor thermometry, which offers an option of accurate and contactless temperature determination under high environmental noise. We studied YAG:Dy as thermographic phosphor at an excitation wavelength of 405 nm. We tested our approach under different experimental conditions with noise levels of about 550, 1060 and 2190 times larger than the excitation signal. With the dual-channel lock-in setup, we were able to suppress the strong noise in all cases and to reliably determine surface temperature using our optical measurements (error < 10 K). Additionally, the effect of signal to noise ratio, lock-in frequency and lock-in bandwidth on temperature determination accuracy was studied in this work.

Keywords: phosphor thermometry, luminescence, lock-in, dual-channel, temperature

(Some figures may appear in colour only in the online journal)

Introduction

Energy conversion processes play an essential role in everyday life. They tend to strongly depend on temperature. As an example, just consider the efficiencies of photovoltaic modules, engines or turbines. Accordingly, non-invasive temperature measurement is a beneficial tool for understanding and optimizing a huge variety of applications for energy conversion [1, 2]. With the variety of applications also the working temperatures of the different energy conversion systems differ from each other. For example, photovoltaic modules work typically at temperatures from around room temperature to up to about 100 °C [3, 4], whereas engines in cars work typically at around 400 °C–600 °C [5, 6] and the blades of turbines at around 1000 °C [7]. Regarding energy conversion via 'classic' thermodynamic processes, higher temperatures are desired as the Carnot efficiency increases with larger temperature gradients [8]. Optimal temperatures for concentrated solar thermal power plants, for example, show values at about 1000 °C and above (the thermal losses due to infrared (IR) radiation levels the optimal temperatures off) [9].

The most common method of measuring contactless surface temperature is IR-thermography. IR-thermography exploits the fact that a hotter surface emits more IR-radiation (and showing a shift in the emission spectrum) [10]. This method has been successfully applied in numerous cases and experiments. However, it is a passive measurement method and the signal intensity only depends on the temperature of the

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Surface thermography using dual channel imaging based on the blue and red emission of $Ba_3MgSi_2O_8$:Eu^{2+}, Mn^{2+}

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Abstract

In this investigation, we present a surface temperature determination method based on the luminescence characteristics of $Ba_3MgSi_2O_8$:Eu^{2+}, Mn^{2+}. Simple optics utilizing only one RGB scientific CMOS camera makes this measurement technique easily applicable. Four different imaging methods were developed and are presented together with the corresponding calibration curves. We successfully utilized the methods to take a surface temperature distribution image on glass plates with a point heat source between them.

Keywords: phosphor spectroscopy, dual channel lock-in method, phase sensitive averaging detection method, imaging, temperature measurement, photoluminescence decay, intensity ratio

(Some figures may appear in colour only in the online journal)

Introduction

Temperature measurement plays a significant role in energy technology [1, 2] and mechanical engineering, equally contributing to the development and application of energy storage and photovoltaic systems, engines, and turbines. Temperature measurement and control plays a significant role in medicine [3, 4], not only for diagnostic purposes, but also for cancer treatment by local heating and laser surgery. Non-invasive, contactless surface temperature determination methods are interesting for research and industry. Accurate determination of temperature affects the tractability and reproducibility of scientific research, where the measurement of absolute or relative temperature values is necessary for the simulations of thermal conductance [1], chemical reactions [2], and mechanical deformation [3], for the visualization of vapor, gas, and liquid flow [4], determination of the temperature of microparticles in plasmas to improve thin-film deposition [5], or in medical research [6].

Depending on application, the temperature range may be very different: photovoltaic modules work at temperatures around 370 K [7, 8], car engines between 650–900 K [9] and concentrated solar thermal power plants can reach 1300 K [10].

Phosphor thermometry utilizes the temperature dependent transient or steady-state luminescence characteristics of phosphors [11, 12]. The former is the luminescence rise or decay time [13]. The latter correlates the intensity of the emission peaks with the temperature. Respectively, pulsed or continuous excitation is used [14].

Photoluminescence intensity and its transient features depend on the temperature because of the Boltzmann distribution between the energy levels, temperature-dependent probability of the radiative and non-radiative transitions, and thermal shift of the energy levels involved in the process [18, 19].

Several authors have utilized color cameras for thermographic purposes. As an example, an RGB CCD camera has

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Nitrides

Ammonothermal Synthesis of Earth-Abundant Nitride Semiconductors $ZnSiN_2$ and $ZnGeN_2$ and Dissolution Monitoring by In Situ X-ray Imaging

Jonas Häusler,[a] Saskia Schimmel,[b] Peter Wellmann,[b] and Wolfgang Schnick*[a]

Abstract: In this contribution, first synthesis of semiconducting $ZnSiN_2$ and $ZnGeN_2$ from solution is reported with supercritical ammonia as solvent and KNH_2 as ammonobasic mineralizer. The reactions were conducted in custom-built high-pressure autoclaves made of nickel-based superalloy. The nitrides were characterized by powder X-ray diffraction and their crystal structures were refined by the Rietveld method. $ZnSiN_2$ ($a=5.24637(4)$, $b=6.28025(5)$, $c=5.02228(4)$ Å, $Z=4$, $R_{wp}=0.0556$) and isotypic $ZnGeN_2$ ($a=5.46677(10)$, $b=6.44640(12)$, $c=5.19080(10)$ Å, $Z=4$, $R_{wp}=0.0494$) crystallize in the orthorhombic space group $Pna2_1$ (no. 33). The morphology and elemental composition of the nitrides were examined by electron microscopy and energy-dispersive X-ray spectroscopy (EDX). Well-defined single crystals with a diameter up to 7 μm were grown by ammonothermal synthesis at temperatures between 870 and 1070 K and pressures up to 230 MPa. Optical properties have been analyzed with diffuse reflectance measurements. The band gaps of $ZnSiN_2$ and $ZnGeN_2$ were determined to be 3.7 and 3.2 eV at room temperature, respectively. In situ X-ray measurements were performed to exemplarily investigate the crystallization mechanism of $ZnGeN_2$. Dissolution in ammonobasic supercritical ammonia between 570 and 670 K was observed which is quite promising for the crystal growth of ternary nitrides under ammonothermal conditions.

Introduction

Gallium nitride and respective solid solutions (Al,Ga,In)N represent one of the most important materials for optoelectronic semiconductor devices. The development of new semiconducting materials is a key aspect of current research due to the rapidly growing market, the increasing number of application fields, and in addition the scarcity of elements like gallium and indium. Recently, various ternary zinc nitrides have been screened in terms of electronic structure, dopability, and stability using first-principle calculations.[1] In particular, the Grimm–Sommerfeld analogous compounds $Zn(Si,Ge,Sn)N_2$ feature similar structural, optical, and electronic properties to (Al,Ga,In)N.[2,3] Promising superior properties have been predicted as well, such as similar spontaneous polarization parameters which could diminish the issue of polarization fields in heterostructures.[3,4] The ternary zinc nitrides also offer excellent band gap tunability and additional substitution sites, which enable a further modification of the electronic band structure. Besides, they are comprised of earth-abundant elements and feature high chemical and thermal stability.

About 25 years ago, Endo et al. demonstrated the synthesis of $ZnSiN_2$ and $ZnGeN_2$ using a high-pressure belt-type apparatus.[5] Powder samples were synthesized starting from the binary nitrides at pressures up to 6.5 GPa and temperatures between 1300 and 1900 K. With the exploration of the semiconducting properties, these compounds attracted increasing interest, which promoted the development of new epitaxy processes. Thin films of $ZnMN_2$ (M = Si, Ge, Sn) can be deposited on specific substrates by metalorganic vapor phase epitaxy (MOVPE) or molecular beam epitaxy (MBE) techniques.[6–8] However, no synthetic approach for the growth of bulk single crystals of these ternary nitrides have been developed as yet.

Ammonothermal syntheses comprise solvothermal reactions using supercritical ammonia as the solvent. In analogy to the well-studied hydrothermal crystal growth of quartz, single crystals of binary nitrides like AlN and GaN can be grown from solution by convection-driven chemical transport reactions.[9] The autoclaves are sectioned in dissolution and growth zones applying specific temperature gradients. Specially designed baffle plates are used to reach a constant temperature around the crystallization seed and to control the convection flow of the supercritical fluid. Mineralizers like alkali metal amides or ammonium halides are added to increase the solubility of the starting materials and to form intermediates, which also act as transporting agents.

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Pinhole-Free Inkjet Printing Strategies for Organic Electronics

Armin Heinrichsdobler, Julia Christina Roigk, Frank Schirmeier, Christoph Josef Brabec, and Thomas Wehlus*

Inkjet printing is a widely used technique in the field of printed electronics. Yet its reliability is limited because absent droplets induced by defective, e.g., clogged, nozzles can lead to pinholes in the printed layers causing a reduction of the quality of printed films or a breakdown of the functionality in microelectronic devices. Therefore, pinholes in inkjet-printed layers need to be avoided. In this study the origins for pinholes in inkjet-printed films are examined. It is found that single missing droplets cannot lead to pinholes but certain formations can. This paper presents the corresponding responsible combinations of defective nozzles necessary to create a pinhole. To enable a statistical approach the pinhole occurrence probabilities are computed depending on the number of broken nozzles as well as quality factors and step sizes with a Monte Carlo simulation. The model shows that by choosing the right print strategy the pinhole probability can be reduced by three orders of magnitude. Finally, a novel print strategy is suggested, which is not yet supported by default printer settings but can reduce the pinhole probability even further by a factor of over 2000 in total. This represents the smallest pinhole occurrence probability ever achieved.

1. Introduction

Inkjet printing has become an important technology for flexible and organic electronics[1–7] and is considered to extend its market share to more than 18% compared to other printing technologies in the field of printed electronics until the end of the decade.[8]

The appeal of this technology compared to other microstructuring techniques such as photolithography, screen printing, or spray coating lies in the possibility to deposit functional material on-demand by a mask- and contactless process. Inkjet as a digital printing process is very cost-efficient: materials are deposited directly onto the substrate in a one-step-process which significantly reduces material waste and process complexity. It also enables high process flexibility since the form and shape of the fabricated layers can be easily and quickly changed batch to batch.[7]

Despite these advantages inkjet printing also has its challenges. One critical issue is nozzle clogging, which leads to sporadic misfiring or jetting failures even if the inkjet ink formulation is well-designed.[9–11] The exact causes for these firing defects have not yet been completely understood,[11,12] yet numerous effects leading to nozzle clogging have been identified.[9–20] A very general cause of nozzle failure is drying of the applied inkjet ink for water- and volatile solvent-based inks or partial curing of UV-curable inks, which can lead to attachment of solid material at the nozzle orifice blocking the nozzle jetting either partially or completely.[11–13] Another reason is precipitation of material at the nozzle wall or the blocking of the nozzle channels from the inside by particle agglomeration.[9] In colloidal systems clogging may also occur by shear-induced gelation or hydrodynamic bridging.[9,14–17] Furthermore, jetting failure can also be induced by residual air or gas bubbles in the printhead.[9,18–20] Blocked nozzles can oftentimes be relieved by proper maintenance of the printhead. However, avoidance of printing defects by cleaning is not always possible, for example, when the clogging happens spontaneously during a printing process or when the remaining solid at the nozzle orifice or within the microchannels of the head is completely dried up and cannot be removed any more. Printheads are considered to be consumables. Usually the number of functional nozzles of a printhead degrades over time either due to material wear or due to unresolvable nozzle blockage.

Obviously stable and reliable droplet jetting is required for a successful upscaling of inkjet technology but misfiring or jetting breakdown can in general not be prevented completely.[21] One way to reduce the failure rate in inkjet printing is optical or acoustic sensing of nozzle functionality and automatic deactivation or readjustment of the nozzles.[22,23] However, these methods are rather complex and expensive and it would be desirable to enhance stability of inkjet printing directly by the process.

More explicitly, defective nozzles can generate unintended holes within the printed films which negatively influence the film functionality, quality or visual appearance of the layers. In order to enable stable inkjet mass production unintended pinholes need to be avoided. However, the explicit origins of pinhole creation in inkjet-printed layers, e.g., the arrangements of broken nozzles necessary for pinholes to be generated, as well as tactics to overcome these defects have not been paid much attention.

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Influence of the Hole Transporting Layer on the Thermal Stability of Inverted Organic Photovoltaics Using Accelerated-Heat Lifetime Protocols

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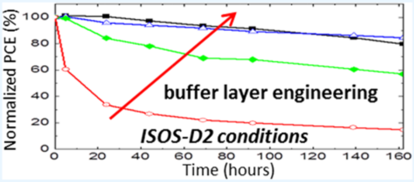

ABSTRACT: High power conversion efficiency (PCE) inverted organic photovoltaics (OPVs) usually use thermally evaporated MoO_3 as a hole transporting layer (HTL). Despite the high PCE values reported, stability investigations are still limited and the exact degradation mechanisms of inverted OPVs using thermally evaporated MoO_3 HTL remain unclear under different environmental stress factors. In this study, we monitor the accelerated lifetime performance under the ISOS-D-2 protocol (heat conditions 65 °C) of nonencapsulated inverted OPVs based on the thiophene-based active layer materials poly(3-hexylthiophene) (P3HT), poly[[4,8-bis[(2-ethylhexyl)oxy]benzo[1,2-*b*:4,5-*b*′]dithiophene-2,6-diyl][3-fluoro-2-[(2-ethylhexyl)carbonyl]thieno[3,4-*b*]thiophenediyl]] (PTB7), and thieno[3,2-*b*]thiophene-diketopyrrolopyrrole (DPPTTT) blended with [6,6]-phenyl C_{71}-butyric acid methyl ester (PC[70]BM). The presented investigation of degradation mechanisms focus on optimized P3HT:PC[70]BM-based inverted OPVs. Specifically, we present a systematic study on the thermal stability of inverted P3HT:PC[70]BM OPVs using solution-processed poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS) and evaporated MoO_3 HTL. Using a series of measurements and reverse engineering methods, we report that the P3HT:PC[70]BM/MoO_3 interface is the main origin of failure of the P3HT:PC[70]BM-based inverted OPVs under intense heat conditions, a trend that is also observed for the other two thiophene-based polymers used in this study.

KEYWORDS: *organic photovoltaics, inverted structure, thermal stability, ISOS-D-2 protocol, lifetime, degradation mechanism, hole-transporting layer, buffer layer engineering*

1. INTRODUCTION

Organic photovoltaics (OPVs) have attracted great scientific interest during the past decade because of their ease of manufacture with printable techniques and their potential to become flexible, lightweight, and low-cost energy sources.[1,2] High power conversion efficiencies (PCEs) and prolonged lifetimes are essential for OPV commercialization. Exciting PCEs of 10% have been demonstrated,[3] but long stabilities of OPVs are the next barrier that needs to be overcome. Understanding the degradation mechanisms that influence the stability of different device configurations under various environmental stress factors is still a challenging task.

In the inverted structure,[4,5] the use of an air-stable metal such as silver results in enhanced lifetime compared with normal structured OPVs, which are limited in stability mainly because of the oxidation of the metals such as calcium or aluminum.[6] Poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS) is the most common material used as the hole-transporting layer (HTL) in both architectures. It is known that because of its hygroscopic nature, ingress of moisture and oxygen from the edges into the device can cause degradation.[7,8]

Furthermore, heat is one of the environmental factors found to significantly affect the long-term stability of OPVs. Heat stability studies at the operating temperature performed by

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Influence of codoping on the luminescence properties of YAG:Dy for high temperature phosphor thermometry

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ABSTRACT

The effects of codoping on the temperature-dependent luminescence of YAG:Dy were investigated for application in high temperature thermometry. YAG:Dy is a well-known thermographic phosphor suitable for high temperature measurements. However, its decay time is too long for studying temperatures in fast transient technical processes. Codoping is a known method for increasing the signal intensity and for decreasing luminescence decay times. Five co-doped samples with three different sensitizers, namely Tm, Tb and Pr were synthesized by solid-state method. Changes in spectral emission behavior and temperature dependent decay time are presented up to 1600 K. The intensity ratio used for temperature measurements was similar for all samples, and decay time decreased for all codopings. Codoping by Tm decreased signal intensity considerably, thus YAG:Dy,Tm is not suitable for high temperature measurements. However, codoping YAG:Dy with Tb and especially Pr resulted in improved luminescent characteristics, and these phosphors are promising for high temperature phosphor thermometry.

1. Introduction

Thermographic phosphor thermometry has become an established technique for remote and non-intrusive temperature measurements. The phosphors employed usually consist of a ceramic powder host matrix doped with a rare-earth or transition metal activator. They are means to provide temporally and spatially resolved temperature fields for both surface temperature measurements [1] as well as for thermometry of gaseous flows [2–4].

Depending on the technical application studied, phosphors with different characteristics such as temperature sensitivity range, decay time, luminescence intensity, emission wavelength or cross sensitivities are needed. Investigation of the thermographic properties for various phosphors were presented by Allison and Gillies [4] and Aldén et al. [5]. An overview over the decay time characteristics of different phosphor materials is given in [1]. An extensive summary on phosphor applications for different temperature ranges can be found in [6,7]. The phosphorescent materials mainly used for high temperature thermometry are presented in Table 1. The widest temperature range is covered by YAG:Dy and YAG:Tm showing temperature dependent exposure times of 1–10^3 µs or 0.1–10^2 µs, respectively.

The luminescence properties of thermographic phosphors strongly depend on the interaction between host lattice and dopant ions. As a rule, rare earth activators have a weak coupling of the 4f electrons with the lattice. This results in narrow emission lines and higher thermal quenching temperatures, which is advantageous in comparison to transition metals [22]. The YAG crystal structure is body-centered cubic, with the rare earth dopant substituting ^{3}Y at the dodecahedral ^{3}Y-sites in the crystal lattice [23].

In general, increasing temperature influences the spectral behavior of rare earths. Thermalization effects occur when two energy levels lie relatively close together, as for example the $^4F_{9/2}$ and the $^4I_{15/2}$ energy levels of YAG:Dy. At higher temperatures the population of higher energy levels rises, changing the intensity distribution of the spectrum corresponding to Boltzmann's law. The radiative transition decay time is reduced due to quenching, vibrational relaxation and internal conversions. Additionally, broadening of linewidth becomes more pronounced caused by lattice vibrations [24].

The Dieke diagram can help to understand the emission behavior of the activator ions. An excerpt for the four studied rare earths, namely Dy^{3+}, Pr^{3+}, Tm^{3+} and Tb^{3+} is given in Fig. 1.

$Y_3Al_5O_{12}$ (YAG) has proven to be an efficient host for high

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Suppression of Hysteresis Effects in Organohalide Perovskite Solar Cells

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Thin-film solar cell based on hybrid perovskites shows excellent light-to-power conversion efficiencies exceeding 22%. However, the mixed ionic-electronic semiconductor hybrid perovskite exhibits many unusual properties such as slow photocurrent instabilities, hysteresis behavior, and low-frequency giant capacitance, which still question us so far. This study presents a direct surface functionalization of transparent conductive oxide electrode with an ultrathin ≈2 nm thick phosphonic acid based mixed C60/organic self-assembled monolayer (SAM) that significantly reduces hysteresis. Moreover, due to the strong phosphonates bonds with indium tin oxide (ITO) substrates, the SAM/ITO substrates also exhibit an excellent recyclability merit from the perspective of cost effectiveness. Impedance studies find the fingerprint of an ion-based diffusion process in the millisecond to second regime for TiO_2-based devices, which, however, is not observed for SAM-based devices at these low frequencies. It is experimentally demonstrated that ion migration can be considerably suppressed by carefully engineering SAM interfaces, which allows effectively suppressing hysteresis and unstable diode behavior in the frequency regime between ≈1 and 100 Hz. It is suggested that a reduced density of ionic defects in combination with the absence of charge carrier accumulation at the interface is the main physical origin for the reduced hysteresis.

The booming of hybrid organohalide lead perovskites in the past few years attracted the broad interest in photovoltaics (PVs) and other optoelectronics research community.[1–7] This is not only because of its unprecedented rate of development compared with other traditional PV technologies such as GaAs, Si, or CIGS (copper indium gallium (di) selenide) or even the new generation PVs including dye-sensitized solar cells, organic solar cells, and quantum dot solar cells, but also the combination of multiple benign properties including high absorption coefficient,[8] ambipolar transport characteristics,[9] low Urbach energy,[8,10] long charge carrier diffusion length,[11] and recently reported "photon recycling,"[12] making it as a most suitable semiconductor for many optoelectronic applications. On the other hand, this kind of material also exhibits some unique characteristics, including the slow photoconductivity response,[13] j–V hysteresis,[14] and the switchable photocurrent,[15] which has not often been observed in other traditional PV technologies before. Among these unresolved issues, hysteresis is one of the most crucial effects. Due to the j–V curves dependence on sweeping directions and rates, the performance of solar cells cannot be accurately evaluated. Early explanations for the origin of photocurrent hysteresis included ferroelectricity,[16] charge trapping-detrapping,[14] and migration of ions or ionic defects.[17–20] Ferroelectricity from ferroelectric nanodomains would unlikely influence the solar cell

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A generic interface to reduce the efficiency-stability-cost gap of perovskite solar cells

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A major bottleneck delaying the further commercialization of thin-film solar cells based on hybrid organohalide lead perovskites is the interface losses in state-of-the-art devices. We present a generic interface architecture that combines solution-processed, reliable, and cost-efficient hole-transporting materials, without compromising efficiency, stability or scalability of perovskite solar cells. Tantalum doped tungsten oxide (Ta-WO_x)/conjugated polymer multilayers offer a surprisingly small interface barrier and form quasi-ohmic contacts universally with various scalable conjugated polymers. Using a simple regular planar architecture device, Ta-WO_x doped interface-based perovskite solar cells achieve maximum efficiencies of 21.2% and combined with over 1000 hours of light stability based on a self-assembled monolayer. By eliminating additional ionic dopants, these findings open up the whole class of organics as scalable hole-transporting materials for perovskite solar cells.

Thin-film solution-processed solar cells based on a hybrid organohalide lead perovskite semiconductor have achieved certified power conversion efficiencies (PCEs) exceeding 22% (*1*). Early efforts to bring this technology from the lab to the market quickly revealed certain disadvantages of perovskites, including the use of toxic lead, the diffusion of ionic defects causing a hysteresis effect, long-term stability, water sensitivity, the complexity of the ink formulation, as well as the cost efficiency and compatibility of the interface materials (*2*–*12*). Of these, a critical limitation on commercializing this technology is the absence of suitable hole-transporting materials (HTMs) that offer full performance without sacrificing long-term stability, and with low material costs and printability from green solvents.

At present, state-of-the-art devices still use HTMs such as 2,2′,7,7′-tetrakis[*N*,*N*-di(4-methoxyphenyl)amino]-9,9′-spirobifluorene (spiro-MeOTAD) and poly[bis(4-phenyl)(2,4,6-trimethylphenyl)amine] (PTAA), where additives such as lithium salts, cobalt complex, and 4-*tert*-butyl pyridine (TBP) are often used to enhance device efficiency. However, lithium salts and TBP can cause intensive degradation processes within of the device. Therefore, attention has increasingly turned to the development of ionic dopant-free HTMs. Indeed, several groups have observed that stability is enhanced when dopants are either removed from the organic HTMs or totally avoided. However, all of these methods compromise device efficiency (*13*–*15*). Alternative bilayer approaches that use a thermally evaporated MoO_x have given excellent time-zero performance but suffer from fast degradation (*16*, *17*). Current material engineering strategies, such as adding cross-linking agents to HTMs, enhance the stability of the active material (*18*); this is, however, at the cost of more complex processing and a still unsatisfactory protection of the fairly reactive MoO_x against perovskite's ionic complexes (*17*).

In addition to stability, the costs, the solubility, the processing properties as well as the scalability of spiro-MeOTAD and PTAA are limited and do not fulfill the requirements for large area module processing. High web speed is desired in high-throughput processing methods such as roll-to-roll coating, not to mention the increased fabrication complexity because of the short shelf life of doped HTM inks and the required slow oxygen doping process (*19*). Carbon-based π-conjugated semiconductors have been widely investigated in the past 20 years of organic photovoltaic (OPV) and organic

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Excited-State Interaction of Semiconducting Single-Walled Carbon Nanotubes with Their Wrapping Polymers

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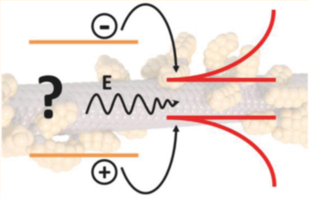
Supporting Information

ABSTRACT: We employ photoluminescence and pump−probe spectroscopy on films of semiconducting single-walled carbon nanotubes (CNTs) of different chirality wrapped with either a wide band gap polyfluorene derivative (PF12) or a polythiophene with narrower gap (P3DDT) to elucidate the excited states' interplay between the two materials. Excitation above the polymer band gap gives way to an ultrafast electron transfer from both polymers toward the CNTs. By monitoring the hole polaron on the polymer via its mid infrared signature, we show that also illumination below the polymer band gap leads to the formation of this fingerprint and infer that holes are also transferred toward the polymer. As this contradicts the standard way of discussing the involved energy levels, we propose that polymer-wrapped CNTs should be considered as a single hybrid system, exhibiting states shared between the two components. This proposition is validated through quantum chemical calculations that show hybridization of the first excited states, especially for the thiophene−CNT sample.



Polymer-wrapped semiconducting single-walled carbon nanotubes (CNTs) attract considerable research interest because they allow for solution deposition, possibly on flexible substrates, and are stable under environmental conditions. Crucially, the wrapping polymer not only promotes stability of the suspension but also serves as a sensitive tool to select semiconducting tubes, which are generally mixed with metallic ones after synthesis.[1,2] This selectivity is a key reason for an improved performance of CNT electronic devices, for example, field effect transistors or photodetectors.[3−6] While charge conduction in this composite system is commonly discussed as if the polymer chains were absent, the close proximity of the two components and their π-electron systems suggest otherwise.

Consequently, photoluminescence (PL) spectroscopy of films of polymer-wrapped CNTs often reveals a shortening of polymer PL lifetime, when compared to the neat material. This effect was previously attributed to a rapid energy or electron transfer toward the CNTs.[7−10] It is of utmost importance to understand this interaction in greater detail, especially when developing electro-optical applications involving charge transport through networks of polymer-wrapped CNTs.

Here, we report on the photophysical behavior of polymer-wrapped semiconducting CNT films. Using a Fourier transform infrared (FTIR) spectrometer, we measure the steady-state photoinduced absorption down to energies as low as 0.07 eV. In this spectral region, we observe the polymer's polaron absorption, which we use to monitor charge-transfer processes. Additionally, we employ ultrafast transient PL and absorption spectroscopy to further elucidate the interplay of the two components and employ quantum chemical calculations to validate our theory. As model polymers, we chose a wide band gap polyfluorene (poly(9,9-didodecylfluorene-2,7-diyl, PF12) and a polythiophene derivative (poly(3-dodecylthiophene), P3DDT) with narrower band gap, both of which are able to efficiently select semiconducting CNTs.[5]

We find long-lasting ground-state bleaches and photoinduced absorptions to form for all chiralities at all employed excitations. The strength of the respective bleaches follows the absorption spectrum, hence demonstrating that fast intertube energy transfer toward narrow band gap tubes is not dominant in our films, which is contrary to other groups' reports on similar systems.[11,12] More importantly, we report the distinct polymer-specific polaron signature in the mid infrared

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Revealing Trap States in Lead Sulphide Colloidal Quantum Dots by Photoinduced Absorption Spectroscopy

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Due to their large surface to volume ratio, colloidal quantum dots (CQDs) are often considered to exhibit a significant amount of surface defects. Such defects are one possible source for the formation of in-gap states (IGS), which can enhance the recombination of excited carriers, i.e., work as electrical traps. These traps are investigated for lead sulphide CQDs of different size, covered with different ligands using a mid-infrared photoinduced absorption (PIA) technique. The obtained PIA spectra reveal two distinct absorption bands, whose position depends on the particle size, i.e., the electronic confinement in the CQDs. Smaller particles exhibit deeper traps. The chemical nature of the capping ligand does not affect the resulting position other than due to its change in confinement, but better passivating species lead to smaller signals. Furthermore, ligand specific narrow lines observed are superimposed on the broad electronic background of the PIA spectra, which is attributed to Fano resonances caused by the interplay of the narrow molecular vibrations and the continuum of trap states. Mid-infrared photoinduced absorption represents a valuable tool to unravel distributions of IGS in CQDs and allows for an assessment of the quality of ligand exchanged films. These findings have implications for understanding the performances of CQD-based (opto-) electronic devices, such as solar cells, transistors, or quantum dot light emitting diodes, which are limited by frequent carrier trapping events.

1. Introduction

Colloidal quantum dots (CQDs) are often based on either II–VI or VI–VI semiconductors–predominantly cadmium or lead chalcogenides (PbX, CdX). These classes of materials are highly attractive for applications in the field of (opto-)electronics– mostly due to the feasible processing from solution and the tunability of their bandgap energy. Lead sulphide (PbS), in particular, attracts considerable interest due to its narrow bulk bandgap of 0.41 eV and the subsequent possibility to harness infrared photons in detectors and solar cells[1–4] or emit infrared light.[5–7]

As-synthesized CQDs are commonly covered with long, electrically insulating surface ligands that need to be exchanged in order to promote electrical conduction. This exchange improves the charge carrier mobility, but can simultaneously affect the quantum dot (QD) density of states (DOS) and may introduce in-gap states (IGS).[8] In most cases, IGS are considered as trap states. The high surface to volume ratio renders the CQDs vulnerable to surface-related defects, which might be caused by incomplete surface passivation, surface oxidation, or interfacial states caused by the attachment of exchanged ligands. Such defect states were observed for PbS before by various techniques. Reported were especially a state 0.2 eV above the valence level of 1,2-ethanedithiol or 1,3-mercaptopropionic acid (EDT, MPA) capped CQDs via Kelvin probe force microscopy (KPFM) and scanning tunneling spectroscopy (STS),[9–12] Additionally, a quasimetallic midgap band ≈0.4 eV below the conduction level for EDT capped PbS was reported for electron transport experiments.[13,14] For PbS treated with tetrabutylammonium iodide (TBAI) a trap distribution with

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Panchromatic ternary/quaternary polymer/fullerene BHJ solar cells based on novel silicon naphthalocyanine and silicon phthalocyanine dye sensitizers†

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More efficient light harvesting throughout the whole solar spectrum by introducing third and fourth components offers a new pathway towards the development of high efficiency organic solar cells based on polymer/fullerene blends. Recently, dye molecules have been utilized as promising light harvesting photosensitizers in the near-IR region. Herein, we report the design, synthesis and application of a novel silicon naphthalocyanine (**SiNC-1**) as an efficient photosensitizer in single dye ternary devices as well as in multi-colored co-sensitized quaternary devices, incorporating a silicon phthalocyanine (**SiPC-0** or **SiPC-1**) as the fourth component to complement the spectral absorption of the **SiNC-1**. The dominant complex charge transfer/transport mechanism behind the enhanced photosensitivity of the ternary blend has been investigated by means of electrical, optical, and advanced characterization techniques. External quantum efficiency (EQE) measurements on multi-colored dye sensitized devices covering the UV-vis as well as near-IR regions from 350 up to 900 nm outline apparent signal characteristics of each single dye, corroborating the effective contribution of both **SiPC** and **SiNC** dyes to enhancing the short-circuit current density (J_{SC}). Our results further illustrate the potential of the multi-colored dye sensitization concept as a powerful approach to mitigate the non-ideal optical absorption normally encountered in organic-based optoelectronic devices.

Introduction

Bulk heterojunction (BHJ) solar cells based on polymer/fullerene blends have attracted much attention over the past decade, leading to a breakthrough in power conversion efficiency (PCE) of over 10%.[1–5] Higher PCEs are now achieved using low-bandgap polymers that allow harvesting a broader fraction of the solar spectrum.[6,7] Since common polymers such as regioregular poly(3-hexylthiophene, P3HT) absorb only a quarter of the total photons in the terrestrial solar light spectrum,[8] more efficient light harvesting is required to optimize absorption in BHJs. Several strategies are currently being pursued to achieve enhanced PCE. One possible solution is through employing conjugated polymers with smaller band gaps with absorption ranges extending into the near-IR region.[9–13] Alternatively, the tandem concept, which involves stacking two or more cells with complementary absorption spectra in series or parallel connection, could be another successful approach.[14–17]

The formation of BHJ devices from ternary blends using a third component to act as the second donor or acceptor material (with different optical properties) has been intensively studied.[18–24] These reports show that dye sensitization is a promising way to improve light harvesting. Recently, a variety of dye molecules have been designed and synthesized to act as light-harvesting photosensitizers in the longer wavelength region of the spectrum,[25,26] and the photophysics of systems composed of, for example, polymer/dye/fullerene blends has been studied.[27–29] Little is known, however, about the details of the overall charge transfer/transport mechanism and the role of dyes in ternary blends.

To the best of our knowledge, some dye molecules have successfully been applied for ternary blend systems, while the

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Synthesis and luminescent properties of prospective Ce^{3+} doped silicate garnet phosphors for white LED converters

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ABSTRACT

The results on crystallization and investigation of the luminescent properties of prospective ceramic phosphors based on the Ce^{3+} doped {Ca2R}[ScB](CSi2)O12 (R = Lu, Y, Gd; B = Sc, Ga, C = Ga, Al) silicate garnets are presented for the first time in this work. We have observed the variations of the spectroscopic properties of Ce^{3+} ions in the mentioned Ca^{2+}-Si^{4+} garnet hosts depending on the cation content at the dodecahedral {}, octahedral [] and tetrahedral () sites of garnet lattice. These results can be useful for the development of new generation of ceramic phosphor converters for white LEDs based on the garnet compounds under study.

1. Introduction

In the last two decades the lamps based on the white light emitting diodes (WLED) have displaced the traditional light sources due to their advantages including high luminous efficiency, energy saving, long lifetime and environmental friendliness. The rate of such a displacement for various applications such as backlighting for displays, automotive and general lighting depends on developing more powerful blue and near UV emitting chips, more efficient phosphors and new schemes for conversion of chip radiation to the white light [1].

At present, a WLED source, manufactured on the basis of a blue LED chip and the yellow emitting YAG:Ce powder phosphor dispersed in epoxy and silicone resin, is a canonical device [2]. While a large number of other different phosphors have been developed to date, YAG:Ce is still the most popular phosphor now for producing the WLED [1,2]. In this context, it should be noted that applying YAG:Ce ceramic or crystal phosphor plates for light conversion in the white LED is now also accessible for manufacturing of high power WLEDs [3]. Therefore, the ceramic phosphors based on different compositions of Ce^{3+} doped $Ln_3Al_5O_{12}$ garnets and techniques for obtaining such phosphor ceramics have been patented repeatedly as well [4].

Due to the flexibility of the garnet structure, which allows replacing ions at the dodecahedral { }, octahedral [ ] and tetrahedral ( ) sites, it is possible to conveniently replace the host cations and modify the $\{Y\}_3[Al]_2(Al)_3O_{12}$ garnet composition for altering the Ce^{3+} spectroscopic properties to better meet the requirements for utilization in WLED. To date the spectroscopic properties of Ce^{3+} in some garnets containing Si^{4+} at tetrahedral sites, namely $Y_3Mg_2AlSi_2O_{12}$, $Y_3MgAl_3SiO_{12}$, $CaY_2Al_4Si\ O_{12}$, $MgY_2MgAl_2Si_2O_{12}$, $CaLu_2Al_4SiO_{12}$, $CaLu_2Mg_2Si3O_{12}$, $Ca_2YMgScSi_3O_{12}$ and $Ca_3Sc_2Si_3O_{12}$ garnets have been published [5–15]. Namely, it has been shown that $Ca_3Sc_2Si_3O_{12}$:Ce exhibits less thermal quenching than YAG:Ce [5]. At the same time, there is no information concerning the spectroscopic properties of Ce^{3+} in silicate garnets of the $\{Ca_2Y\}[Sc,Al,Ga]_2(Ga,Al,Si)_3O_{12}$ family [5–15].

For this reason, this work is devoted to crystallization and investigation of the luminescent properties of phosphors based on the Ce^{3+} doped $\{Ca_2R\}[Sc,B](Ca,Si_2)O_{12}$; R = Lu, Y, Gd; B = Sc, Ga, C = Ga, Al silicate garnets, which can be used for producing high power WLEDs having high color rendering index and low correlated color temperature values [5,6].

2. Samples and method of their preparation

In this work, we report on the first results on the crystallization of ceramics based on the Ce^{3+} doped $\{Ca_2R\}[ScB]_2(CSi_2)O_{12}$; R = Lu, Y,

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Article

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Triphenylamine-Based Push–Pull Molecule for Photovoltaic Applications: From Synthesis to Ultrafast Device Photophysics

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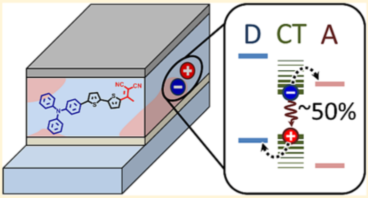
Supporting Information



ABSTRACT: Small push–pull molecules attract much attention as prospective donor materials for organic solar cells (OSCs). By chemical engineering, it is possible to combine a number of attractive properties such as broad absorption, efficient charge separation, and vacuum and solution processabilities in a single molecule. Here we report the synthesis and early time photophysics of such a molecule, TPA-2T-DCV-Me, based on the triphenylamine (TPA) donor core and dicyanovinyl (DCV) acceptor end group connected by a thiophene bridge. Using time-resolved photoinduced absorption and photoluminescence, we demonstrate that in blends with [70]PCBM the molecule works both as an electron donor and hole acceptor, thereby allowing for two independent channels of charge generation. The charge-generation process is followed by the recombination of interfacial charge transfer states that takes place on the subnanosecond time scale as revealed by time-resolved photoluminescence and nongeminate recombination as follows from the OSC performance. Our findings demonstrate the potential of TPA-DCV-based molecules as donor materials for both solution-processed and vacuum-deposited OSCs.

1. INTRODUCTION

The efficiency of bulk heterojunction (BHJ) organic solar cells (OSCs) based on small molecular (SM) donors[1−5] is constantly increasing, with efficiencies of over 10% achieved.[1,6−11] In addition to high efficiencies, SMs demonstrate unique benefits over more conventional polymers such as high purity, batch-to-batch reproducibility, well-defined molecular structure, molecular weight, and so on.[12−14] Moreover, low-molecular-weight SMs make vacuum processability possible,[15−18] which can be utilized to create highly efficient OSCs with low energy disorder to facilitate long-range exciton transport.[19,20]

An important advantage of SMs is flexibility in molecular design,[21] which allows for fine and precise tuning of the chemical and photophysical properties. In the design concept introduced by Tereniziani[22] and Roncali,[23] a triphenylamine (TPA) donor core and dicyanovinyl (DCV) acceptor end groups led to improved solubility, better layer-to-layer stacking in films, and high hole mobility. High performance of >4% in vacuum-evaporated OSCs[24,25] highlights the potential of this approach; however, such molecules potentially suffer from insufficient stability because of the presence of an active vinyl proton in the DCV group. The substitution of the active proton in DCV by an alkyl improves the stability while retaining all other benefits, as has been previously shown for the series of star-shaped[26−31] and linear molecules.[31,32] A similar strategy was very recently undertaken by Bakiev et al.,[33] who reported the synthesis and basic photophysical properties (absorption and photoluminescence spectra in solution) of a TPA-2T-DCV-Me molecule with methyldicyanovinyl as the acceptor group (Figure 1a). This molecule can be considered to be an asymmetrical analog of star-shaped molecule (SSM) N(Ph-2T-DCV-Me)$_3$,[26] which has already demonstrated the power conversion efficiency (PCE) to be as high as 4.8%.

In this work, we extend the synthesis strategy developed recently for the star-shaped[30,31] and linear[31,32] molecules for

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Ligand-assisted thickness tailoring of highly luminescent colloidal $CH_3NH_3PbX_3$ (X = Br and I) perovskite nanoplatelets†

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Quantum size-confined $CH_3NH_3PbX_3$ (X = Br and I) perovskite nanoplatelets with remarkably high photoluminescence quantum yield (up to 90%) were synthesized by ligand-assisted re-precipitation. Thickness-tunability was realized by varying the oleylamine and oleic acid ligand ratio. This method allows tailoring the nanoplatelet thickness by adjusting the number of unit cell monolayers. Broadly tunable emission wavelengths (450–730 nm) are achieved *via* the pronounced quantum size effect without anion–halide mixing.

Hybrid organic–inorganic and all-inorganic metal halide perovskite nanocrystals with the general formula of ABX_3 (A = Cs^+, $NH_2CHNH_2^+$ and $CH_3NH_3^+$; B = Sn^{2+} and Pb^{2+}; X = Cl^-, Br^- and I^-) have been rapidly developed during the last few years.[1–6] The possibility of simple halide compositional mixing enables a wide wavelength tunability (400–800 nm) of the narrow-band emission.[1,3] Furthermore, the high photoluminescence quantum yield (PLQY) of these colloidal nanocrystals reaches up to over 90% without additional surface passivation, demonstrating that dangling bonds do not lead to non-radiative relaxation.[1,7]

Recently, the synthesis of quasi-2D cesium lead halide nanoplatelets (NPLs) with layered structures has been performed using colloidal methods varying the starting ligand ratio, the temperature of the synthesis, the HBr amount, as well as the length of alkylammonium cations and carboxylic acids.[8–13] Concerning the hybrid nanoplatelets (NPLs), only a few papers have demonstrated their thickness tailoring and quantum size effect in suspensions with PLQY $<45\%$.[10,14,15] For example, Cho *et al.*[15] utilized alkylamines with different lengths to achieve the thickness modulation. Sichert *et al.*[10] tuned the ratio of octylammonium bromide and methylammonium bromide for the same purpose. Furthermore, due to the lower stability and sensitivity to moisture of the organolead iodide perovskite colloids,[3,6] the synthesis of the $CH_3NH_3PbI_3$ NPLs with different thicknesses is more challenging.

In this contribution, we present a fast synthesis of nearly monodisperse colloidal $CH_3NH_3PbX_3$ (X = Br and I) organometallic halide perovskite NPLs *via* a ligand-assisted method, enabling monolayer thickness control and leading to a high PLQY of up to 90%.

The synthesis of colloidal $CH_3NH_3PbX_3$ (X = Br and I) NPLs was performed *via* controllable precipitation at room temperature, following a modified approach of Zhang *et al.*[3] The main difference to the method presented in the paper of Zhang is using chloroform as anti-solvent for the $CH_3NH_3PbI_3$ NPLs, and tailoring the size and thickness by varying the oleic acid/oleylamine ligand ratio only for both bromide and iodide NPLs (see the details in the Methods section, ESI†).

The injection of a DMF solution of the $CH_3NH_3PbBr_3$ precursor into toluene rapidly forms highly luminescent NPLs (see the supplementary video, ESI†). By changing the ratio of oleic acid (OA) and oleylamine (OAm) as ligands, we obtained different band gaps as well as luminescence wavelengths of the colloids (Fig. 1a). Upon fixation of the amount of OA in the precursor solution, a certain volume of OAm was added (Table S1, ESI†). This enables a precise tuning of the absorption edge and photoluminescence (PL) of the NPLs from green (514 nm) to blue (447 nm) color. However, beginning from the OA/OAm ratio of 200 μl/30 μl, no further PL shift is observed (peak wavelength at 447 nm, Fig. S1, ESI†). Only the lateral size of the NPLs was further reduced from 10 to 5 nm at OA/OAm = 200 μl/60 μl (shown in Fig. 1d and Fig. 2a). The most challenging task in the synthesis was the cleaning process. Since the organometallic halide perovskite material is highly sensitive to polar solvents and especially water, the conventional

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† Electronic supplementary information (ESI) available: Detailed experimental section with supplementary Fig. S1–S7 and Tables S1–S4. See DOI: 10.1039/c6cc09266g

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Letter

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Brightly Luminescent and Color-Tunable Formamidinium Lead Halide Perovskite $FAPbX_3$ (X = Cl, Br, I) Colloidal Nanocrystals

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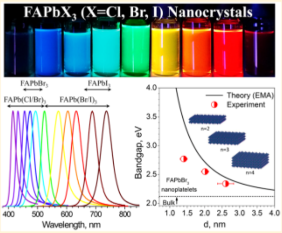
Supporting Information

ABSTRACT: In the past few years, hybrid organic–inorganic and all-inorganic metal halide perovskite nanocrystals have become one of the most interesting materials for optoelectronic applications. Here, we report a facile and rapid room temperature synthesis of 15–25 nm formamidinium $CH(NH_2)_2PbX_3$ (X = Cl, Br, I, or mixed Cl/Br and Br/I) colloidal nanocrystals by ligand-assisted reprecipitation (LARP). The cubic and platelet-like nanocrystals with their emission in the range of 415–740 nm, full width at half-maximum (fwhm) of 20–44 nm, and radiative lifetimes of 5–166 ns enable band gap tuning by halide composition as well as by their thickness tailoring; they have a high photoluminescence quantum yield (up to 85%), colloidal and thermodynamic stability. Combined with surface modification that prevents degradation by water, this nanocrystalline material is an ideal candidate for optoelectronic devices and applications. In addition, optoelectronic measurements verify that the photodetector based on $FAPbI_3$ nanocrystals paves the way for perovskite quantum dot photovoltaics.



KEYWORDS: *Formamidinium, perovskite nanocrystals, optoelectronics, photoluminescence, ligand-assisted reprecipitation*

Formamidinium lead halide perovskites ($CH(NH_2)_2PbX_3$ or $FAPbX_3$, X = Cl, Br, I) are an advanced class of direct bandgap semiconductors for optoelectronic devices, and they have established themselves as a promising alternative for the thermodynamically less stable methylammonium (MA, $CH_3NH_3^+$) perovskites.[1−5] In addition, the hybrid organic–inorganic and all-inorganic metal halide perovskite (ABX_3, where A = Cs^+, $CH(NH_2)_2^+$, $CH_3NH_3^+$; B = Sn^{2+}, Pb^{2+}; X = Cl^-, Br^-, I^-) thin films and their colloidal nanocrystals (NCs) offer a wide variability and multiple opportunities for fine-tuning optoelectronic applications.[6−12] Ease of size control and compositional mixing, band gap, and emission tuning inspired researchers to successfully utilize this material class for efficient solar cells,[13] sensitive photodetectors,[14−18] low threshold lasers,[19,20] laser diodes,[21] advanced photonics,[21] and light-emitting diodes,[9,21,22] as well as for chemical reaction monitoring.[23] Various methods and approaches have been proposed for the synthesis of organic and inorganic metal halide perovskite colloidal nanocrystals ($CsPb(Sn)X_3$, $MAPbX_3$, X = Cl^-, Br^-, I^-) including hot-injection,[6,10,24] ligand-assisted reprecipitation (LARP),[8] or structural conversion of lead halide nanocrystals to perovskite by methylammonium halide incorporation.[25]

Compared to the organic–inorganic MA or all-inorganic Cs perovskite analogues, the pristine formamidinium perovskites have a couple of attractive features like higher thermal, moisture, and chemical stability.[5,11,20,26−29] Nonetheless, compared to the MA perovskite analogues, the preparation technology of thin films,[26] single crystals,[30,31] and microcrystalline powders[2] is not well developed due to the following features: (i) $FAPbI_3$ thin films or crystallites typically crystallize in a "yellow" nonperovskite phase[26,30] after a few hours of storage; (ii) differences in the ionic radii (2.17 Å for MA^+ and 2.53 for FA^+) may affect the growth kinetics.[32] The unique properties of the pristine bulk material inspired us to synthesize and investigate the properties of corresponding colloidal nanocrystals and to establish a new protocol for the synthesis

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OPEN

Abnormal strong burn-in degradation of highly efficient polymer solar cells caused by spinodal donor-acceptor demixing

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The performance of organic solar cells is determined by the delicate, meticulously optimized bulk-heterojunction microstructure, which consists of finely mixed and relatively separated donor/acceptor regions. Here we demonstrate an abnormal strong burn-in degradation in highly efficient polymer solar cells caused by spinodal demixing of the donor and acceptor phases, which dramatically reduces charge generation and can be attributed to the inherently low miscibility of both materials. Even though the microstructure can be kinetically tuned for achieving high-performance, the inherently low miscibility of donor and acceptor leads to spontaneous phase separation in the solid state, even at room temperature and in the dark. A theoretical calculation of the molecular parameters and construction of the spinodal phase diagrams highlight molecular incompatibilities between the donor and acceptor as a dominant mechanism for burn-in degradation, which is to date the major short-time loss reducing the performance and stability of organic solar cells.

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ORGANIC PHOTOVOLTAICS

Washing away barriers

Light-weight and stretchable, organic photovoltaics offer unique integration prospects. Now, organic solar cells and modules can also be washed while maintaining good photoconversion efficiencies.

Ning Li and Christoph J. Brabec

More than 300 GW of photovoltaic (PV) modules had been installed worldwide by the end of 2016, predominantly in solar farms and on rooftops, and predominantly based on silicon technologies. Today, organic PV (OPV) modules are not included in the global roadmap for large-scale PV installations, mainly because of the limited lifetime of current OPV modules. The first commercial OPV products instead entered the portable power market in 2008 and 2009[1]. Since then, OPV technology has continued to develop at pace and with efficiency and lifetime continuously improving, scientists and technology experts are demanding novel and innovative OPV applications for further mass markets. With this goal in mind, Takao Someya and colleagues from the University of Tokyo demonstrate washable and flexible organic solar cells with representative efficiencies of about 7–8% in *Nature Energy*[2].

The current generation of organic solar cells is reaching hero efficiencies on the order of 13% in research laboratories[3–5]. After market implementation in 2009, the efficiency of commercial or close-to-commercial OPV modules has continuously increased from about 2% in 2007[1] to over 8% in 2016[3]. Recent developments in stable and efficient materials[6], electrodes[7] and high-resolution processing[8] strongly suggest that OPV technology will meet the 10% module milestone within the next few years. Importantly, some of the semiconducting materials have the potential to be cheaply produced, and several groups have calculated bill-of-module (BOM) costs between €0.1 per Watt peak (Wp) and €0.5 per Wp at the gigawatt production scale[9]. The BOM is the ratio between the sum of the materials and processing costs per unit area and the electrical energy produced under AM1.5G illumination per unit area. This definition of PV costs is most helpful when comparing modules with different efficiencies, different sizes or simply different PV technologies. Key performance indicators such as competitive efficiencies, BOM predictions of €0.5 per Wp or less, no toxicity and excellent recyclability[10] should position OPV as one of a group of very promising next-generation photovoltaic technologies.

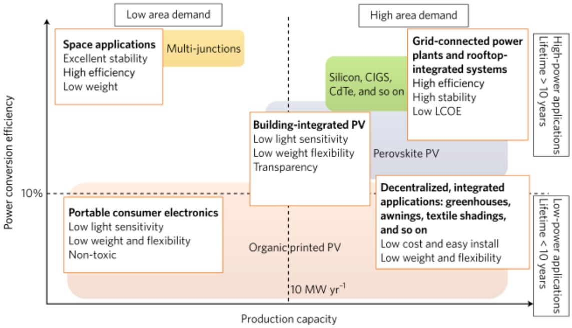

Fig. 1 | Photovoltaic market categorized according to power and area demand. Today's PV roadmap is focused on the high-power and large-area demand region of the graph, serving the enormous demand for renewable, cheap and green grid-connected energy production. OPV modules, on the other hand, will be a major player for decentralized and non-grid-connected applications (module efficiencies below 10 %, module lifetimes shorter than 10 yr). Bags for mobile charging and energy harvesting are applications with a lower area demand, while decentralized solutions for yachting, camping or greenhouses have a significantly larger area demand. That potential for large area demand is considerably enhanced if we further take into account outdoor textiles such as awnings or shadings empowered with integrated flexible and washable OPV modules.

Despite these advantages, we should not expect grid-connected OPV power plants in the near future. This is immediately apparent when comparing the levelized cost of electricity (LCOE) of OPV modules to that of other thin-film technologies such as $CuIn_xGa_{(1-x)}Se_2$ (CIGS) and CdTe. The LCOE is expressed in US cents per kWh and can be calculated by balancing all of the costs for a PV installation over the total, integrated energy yield. Importantly, the LCOE critically depends on the lifetime of the installation[11]. Consequently, until the outdoor lifetime of OPV installations meets the guaranteed 20 year lifetime of competing technologies at BOM costs of €0.5 per Wp or less, grid integration of OPV will not be on the agenda. Today's OPV modules are targeting lifetimes of >5 yr for flexible products and >10 yr for glass-based products. These product lifetimes are considerably shorter than those of competing technologies, calling for totally different, non-grid-connected venues for product development and application design that play to the strengths of OPV modules, including colour, transparency and a fantastic power-to-weight ratio[12], as well as a highly competitive indoor or low-light efficiency of up to 20% (ref. [13]).

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Detailed optical modelling and light-management of thin-film organic solar cells with consideration of small-area effects

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Abstract: We present detailed numerical and experimental investigation of thin-film organic solar cells with a micro-textured light management foil applied on top of the front glass substrate. We first demonstrate that measurements of small-area laboratory solar cells are susceptible to a significant amount of optical losses that could lead to false interpretation of the measurement results. Using the combined optical model CROWM calibrated with realistic optical properties of organic films and other layers, we identify the origins of these losses and quantify the extent of their influence. Further on, we identify the most important light management mechanisms of the micro-textured foil, among which the prevention of light escaping at the front side of the cell is revealed as the dominant one. Detailed three-dimensional simulations show that the light-management foil applied on top of a large-area organic solar cell can reduce the total reflection losses by nearly 60% and improve the short-circuit current density by almost 20%. Finally, by assuming realistic open-circuit voltage and especially the realistic fill factor that deteriorates as the absorber layer thickness is increased, we determine the optimal absorber layer thickness that would result in the highest power conversion efficiency of the investigated organic solar cells.

OCIS codes: (350.6050) Solar energy; (310.0310) Thin films; (290.0290) Scattering; (080.0080) Geometric optics; (120.0120) Instrumentation, measurement, and metrology.

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Noble metal free photocatalytic H_2 generation on black TiO_2: On the influence of crystal facets vs. crystal damage

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In this study, we investigate noble metal free photocatalytic water splitting on natural anatase single crystal facets and on wafer slices of the [001] plane before and after these surfaces have been modified by high pressure hydrogenation and hydrogen ion-implantation. We find that on the natural, intact low index planes, photocatalytic H_2 evolution (in the absence of a noble metal co-catalyst) can only be achieved when the hydrogenation treatment is accompanied by the introduction of crystal damage, such as simple scratching and miscut in the crystal, or by implantation damage. X-ray reflectivity, Raman, and optical reflection measurements show that plain hydrogenation leads to a ≈ 1 nm thick black titania surface layer without activity, while a colorless, density modified, and ≈ 7 nm thick layer with broken crystal symmetry is present on the ion implanted surface. These results demonstrate that (i) the H-treatment of an intact anatase surface needs to be combined with defect formation for catalytic activation and (ii) activation does not necessarily coincide with the presence of black color. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4976010]

In photocatalytic H_2 generation, electron-hole pairs are created by illumination of a suitable semiconductor that is exposed to an aqueous solution; then, subsequent transfer of the excited electrons from the semiconductor conduction band to H_2O then leads to the evolution of H_2. Due to its suitable energetic positions of band edges, high stability, and economic aspects, TiO_2 has been the most studied material for photocatalysis over the last 40 years. Recently, the so-called "black" TiO_2 has attracted wide attention for the photocatalytic generation of hydrogen.[1–5] Specifically, a large body of work addresses the high photocatalytic hydrogen evolution capability when "black" titania is decorated with an adequate noble metal co-catalyst (Pt),[1,5] which is needed to mediate electron transfer from the conduction band to the aqueous environment and as a catalyst for H_2 recombination.

Black TiO_2 was originally produced from anatase nanoparticles by a high pressure hydrogenation (HPH) treatment at elevated temperatures. The black appearance was ascribed to a narrowing of the band-gap of anatase (3.2 eV) to a value of ≈ 1.5 eV, providing visible light absorption. A more recent very attractive finding is that titania crystallite powders, after high pressure hydrogenation, can form an intrinsic, stable co-catalytic feature for H_2 evolution,[6,7] i.e., no noble metal co-catalyst is needed to evolve H_2. Later reports also showed that titania powders or nanotubes, also after H^+ ion implantation[8] or an intense ball milling with TiH_2,[9] can show a similar intrinsic co-catalytic effect.

The majority of work (meanwhile several hundred reports on black TiO_2 have been published) uses polycrystalline anatase (powder, mesoporous structures, and nanotubes).[1–9] In contrast, we address in the present work the question whether specific crystal facets are of crucial importance for the creation of this intrinsic catalytic effect. It is worth noting that for anatase TiO_2, faceting has been reported to significantly affect conventional photocatalytic reaction rates; in general [001] planes are reported to be more reactive than [101] planes.[10]

In our experiments, we used natural anatase crystals and polished [001] wafers obtained from SurfaceNet GmbH, Germany (as shown in Fig. 1). As natural anatase contains small amounts of impurities, giving the crystals a specific color (Mn typically red and Fe typically blue), we used both of these common crystals in our experiments (Fig. 1(a)). In a first set of experiments, the full crystals were hydrogenated at 500 °C at 20 bar, coated with epoxy resin except for the facet of interest, and immersed in a 50 v% MeOH solution (CH_3OH serves here as a hole capture agent) within a sealed quartz tube. Subsequently, the facet of interest was illuminated with a He-Cd laser ($\lambda = 325$ nm, 50 mW, Kimmon, Japan) and hydrogen evolution was measured by gas chromatography and compared to non-hydrogenated crystals. To assess the role of crystal defects, after the initial experiment, the corresponding crystal facet was intensely and randomly scratched using a diamond scribe (Filberschnitt, Carl Rotn GmbH) and is shown in the inset of Fig. 1(a). The crystal was hydrogenated again, and the photocatalytic hydrogen measurement was repeated. After hydrogenation, no apparent change in the defects on the scratched surface was

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Printed semi-transparent large area organic photovoltaic modules with power conversion efficiencies of close to 5 %

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ABSTRACT

Currently, certified lab scale organic photovoltaic (OPV) cells reach efficiencies of more than 12% and life times of 10 years. For commercialization, it is necessary to understand which performance can be reached in fully printed large scale products. Our investigations show that large area, semi-transparent organic photovoltaic modules based on industrially available materials can achieve power conversion efficiencies of more than 4.8% on rigid substrates and 4.3% on flexible ones. The modules processed with a combination of large area coating and laser patterning with an active area of 68.76 cm^2 for flexible modules and a total area of 197.4 cm^2 for glass modules offer exceptionally high geometric fill factors of more than 94% and a transparency of more than 10%. The processing recipe and the layout of the modules are based on indications of optical and electrical simulations which allow to produce devices with only negligible losses in comparison to small single cell devices. Losses due to imperfect coating or patterning are identified by thermal imaging.

1. Introduction

Organic photovoltaics (OPV) offer a broad range of advantages in comparison to other photovoltaic (PV) technologies. OPV is potentially a low cost technology as modules can be produced by a solution based roll-to-roll compatible process, which offers the potential to achieve high processing throughput at low investment cost. Furthermore, unique advantages of the modules like lightness, adjustable colour range and freedom of shape offer the possibility for usage where conventional PV is not applicable. Lab cell devices currently reach power conversion efficiencies (PCE) above 13% for OPV devices and even above 20% for perovskite devices and predicted life times of more than 10 years [1–6]. The continuous progress in single lab cell device efficiencies is based on employing multi-junction stacks needing a sophisticated process which still has not been shown to be transferable to large area processing conditions without considerable losses. Therefore the efficiencies reported for large area processed modules are still significantly lower than those of lab cell devices. This stresses the importance of the development of a stable, reliable production process for minimization of the performance losses. Recently we presented the guidelines for an optimized upscaling route of large area modules which was realized for both, glass and flexible substrates [7,8]. Besides their light weight and their adjustable colour range, one of the big advantages of OPV technology is the possibility to produce semi-transparent modules. This offers new possibilities in applications where conventional PV technologies cannot be used, like integration in facades or windows. Based on an EPIA (European Photovoltaic Industry Association) study, 40% of the European energy demand can potentially be supplied by roof and facade integrated PV. This value corresponds to 1500 GW installed power with a yearly energy production of 1400 TWh [9]. This potential is shared between roofing, walling and glass, where glass has still the highest increase in potential but requires semitransparency.

For semi-transparent applications the transparency of the electrode materials is an essential feature. First semi-transparent organic solar cells (OSCs) with a bilayer photoactive structure, having ITO and silver/ITO as the bottom and top electrodes, respectively, achieved an efficiency of 0.48% and an average

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Gaining further insight into the effects of thermal annealing and solvent vapor annealing on time morphological development and degradation in small molecule solar cells†

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Numerous articles on thermal annealing (TA) and solvent vapor annealing (SVA) treatments have shown that both strategies effectively improve bulk morphology, reduce carrier recombination and thus improve photovoltaic performance of bulk heterojunction (BHJ) organic solar cells (OSCs). In previous work, we found that both TA and SVA treated devices based on a blend composed of a 3-ethyl-2-thioxothiazolidin-4-one containing molecule as donor (named DRCN5T) and [6,6]-phenyl-C$_{71}$-butyric acid methyl ester (PC$_{70}$BM) as acceptor show the similar photovoltaic performance, but their bulk microstructures are difference. Here employing *in situ* photoluminescence (PL) setup and X-ray scattering technologies, we found that the early stages of SVA remarkably affect the surface of film, and in contrast TA affects the whole bulk. Meanwhile, a plurality of experimental results all further confirm the different thermodynamics and kinetics of morphology evolution processed either by TA treatment or SVA treatment. Importantly, it was found that the SVA-treated film showed the increased photo-degradation in devices as compared to the TA-treated layer, resulting from obvious bulk morphology changes under illumination over 500 hours. The aim is to provide comprehensive insight into the influence of TA and SVA on time morphological evolution and degradation in OSCs.

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1. Introduction

Solution-processed bulk heterojunction (BHJ) organic solar cells (OSCs) have attracted extensive attention in the past two decades due to their intrinsic advantages, such as mechanical flexibility, light weightedness, freedom of form, and scalability.[1,2] The combination of a broad understanding of material synthesis, interface and device engineering and physical process control, combined with theoretical studies, has driven the power conversion efficiency (PCE) beyond the 11% milestone.[3–6] Apart from a smart molecular design and device engineering, microstructure engineering is one of the key strategies to achieve well-ordered and crystalline domains as well as effective charge transport properties,[7] allowing to further improve device performance. Generally, BHJ composites comprise binary components and/or multiple components that are arranged in complicated phases,[7] among them several pristine component phases as well as a mixed amorphous or disordered regime resulting from partial miscibility of the components.[8–11] Thus, phase separation is a complex process usually resulting in metastable morphologies, which is determined by the interplay between kinetics (*e.g.* solvent evaporation and molecular ordering), thermodynamics (*e.g.* solubility and miscibility) and other external factors during the drying processes involved in the thin film preparation.[7,11–13]

To date, several strategies to effectively control the nanoscale blend morphology were demonstrated, including additives,[14–16] TA[17–19] and SVA,[8,20,21] *etc.* These morphological control approaches are useful to achieve remarkable interpenetrating network with nanoscale domain sizes as well as a suitable interfacial area, and positively impact the optical and electronic properties of the BHJ blends and also influence their carrier dynamics.[12,22] By reviewing hundreds of publications with respect to the morphological control, we found that TA and SVA as the most common post-treatments applied in BHJ systems, including polymer-fullerene systems,[23] small molecule-

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Evaluation of Electron Donor Materials for Solution-Processed Organic Solar Cells via a Novel Figure of Merit

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Organic photovoltaic (OPV) technology offers many advantages, although no commercial applications have been achieved after more than a decade of intensive research and development. Several challenges have yet to be overcome including high power conversion efficiency (PCE), good processability, low cost, and excellent long-term stability, and so on. In this article, these fundamental challenges are significantly addressed by surveying and analyzing a new merit factor for material applied accessibility containing three parameters: synthetic complexity, device efficiency, and photostability. Thirty-five donor small molecules are introduced to assess their synthetic accessibility. Furthermore, the PCEs and device photostability of these molecules are carried out, and further measured under one sun illumination within 200 h, respectively. Combining with the characteristics of these three factors, investigated molecules are ranked according to an industrial figure of merit (i-FOM), while some guidelines for the material design and synthesis are given. It is suggested that a PCE of >14% and an i-FOM of >20% via active material engineering are realistic for possible industry future of OPV. Along with the systematic study, it is believed that this i-FOM can be taken into consideration at an early stage of molecular design and provides valuable insight for efficient evaluation of photovoltaic materials for possible commercial applications.

1. Introduction

As an important source of renewable energy for a sustainable future, thin-film solution-processed organic photovoltaics (OPVs) have received significant attention due to the advantages of lightweight, mechanical flexibility, low cost, and facile fabrication of roll-to-roll processing as well as substrate and shape freedom.[1–4] During the last two decades, photovoltaic materials are rapidly showing improvements in power conversion efficiencies (PCEs) of over 11% in the OPVs for small area devices (mm^2 scale) with the most promising bulk heterojunction (BHJ) configuration.[5–9] Despite this progress, the widespread commercial application of OPVs has yet to become a reality, and until now only prototypes and demo products with low PCEs of ≈2%–4% have been reported.[10–12] Several fundamental challenges with respect to the product cost, photovoltaic performance, long-term stability, etc., still hamper the up-scale

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Temperature-dependent optical spectra of single-crystal $(CH_3NH_3)PbBr_3$ cleaved in ultrahigh vacuum

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We measure temperature-dependent one-photon and two-photon induced photoluminescence from $(CH_3NH_3)PbBr_3$ single crystals cleaved in ultrahigh vacuum. An approach is presented to extract absorption spectra from a comparison of both measurements. Cleaved crystals exhibit broad photoluminescence spectra. We identify the direct optical band gap of 2.31 eV. Below 200 K, the band gap increases with temperature, and it decreases at elevated temperature, as described by the Bose-Einstein model. An excitonic transition is found 22 meV below the band gap at temperatures <200 K. Defect emission occurs at photon energies <2.16 eV. In addition, we observe a transition at 2.25 eV (2.22 eV) in the orthorhombic (tetragonal and cubic) phase. Below 200 K, the associated exciton binding energy is also 22 meV, and the transition redshifts at higher temperature. The binding energy of the exciton related to the direct band gap, in contrast, decreases in the cubic phase. High-energy emission from free carriers is observed with higher intensity than reported in earlier studies. It disappears after exposing the crystals to air.

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I. INTRODUCTION

Organic-inorganic perovskite semiconductors (OIPS) have opened a whole new field in optoelectronics [1–7]. A comprehensive understanding of the underlying photophysics is still under development. Therefore, detailed knowledge is required of the band structure of OIPS [8–12], modifications by local disorder [13–18], excitonic effects [19–24], polaronic screening [25–28], and their interplay. Many studies that tackle these questions rely on the interpretation of (time-resolved) optical spectroscopy. The experimental data and their interpretation, however, show strong variations. Spectroscopic results obtained from thin films depend on the growth technique [29–33], grain size [30,34], and environmental conditions [35,36].

For example, exciton binding energies between 15 and 84 meV [23,37–42] have been reported for $(CH_3NH_3)PbBr_3$. These variations can be expected to be reduced by studying single crystals [43,44], opening the opportunity to approach the intrinsic photophysics of OIPS. However, the band gaps of $(CH_3NH_3)PbBr_3$ single crystals determined from reflection measurements vary from 2.22 to 2.35 eV [38,39,45–47].

Exposure of crystal surfaces to air results in fast hydration, increasing the room-temperature band gap from 2.22 eV to 2.27 eV [45]. Recent experimental findings made on lead-bromide single-crystals also include the observation of photoluminescence (PL) from high-energy carriers [28] with the potential to enhance solar cell performance, possibly beyond the Shockley-Queisser limit [48]. High-energy carriers have not been apparent to the same degree in earlier studies on thin films. Along another line of research, studies on $(CH_3NH_3)PbI_3$ thin films reveal the coexistence of a direct and an indirect optical band gap with measured energetic spacings of 47 meV [49] and 60 meV [50]. A slightly indirect band gap has been proposed as one of the origins of the low carrier recombination rate found in OIPS [12,14,15]. A possible direct-indirect character of the band gap of related $(CH_3NH_3)PbBr_3$ remains to be investigated. Photoluminescence spectra of $(CH_3NH_3)PbBr_3$ showed a double-peak structure [45,47,51], and further studies are needed to identify its origin.

Perovskite single crystals cleaved in ultrahigh vacuum (UHV) show optical properties at room temperature that are distinctly different from those of thin films and as-grown single crystals [45]. Temperature-dependent measurements can help to develop a more complete picture of these optical properties, which needs to include identification of exciton binding energies, free carriers, as well as direct and possible indirect transitions. Direct measurements of optical absorption spectra of single crystals in transmission are hindered by the short absorption length of visible light in OIPS [52], which forms a basis of their successful application in optoelectronics. Measurements in reflectance are surface-sensitive, and easily affected by hydration of the surface [35,45]. To create clean surfaces and avoid their subsequent hydration, we perform experiments on $(CH_3NH_3)PbBr_3$ single crystals cleaved in UHV. Optical spectra of OIPS single crystals cleaved in UHV have, to the best of our knowledge, only been reported for $(CH_3NH_3)PbBr_3$ at room temperature [45]. We develop an alternative approach to access temperature-dependent optical spectra of OIPS. Therefore, steady-state PL spectroscopy at low excitation density and over a wide temperature range covering two-phase transitions is performed on surfaces of $(CH_3NH_3)PbBr_3$ single crystals cleaved in UHV. These surfaces emit broadband PL light. We also measure bulk-sensitive steady-state PL spectra induced by two-photon absorption (TPI-PL). Because of the vastly different excitation depths, indicated in Fig. 1, absorption spectra can be extracted from the combination of PL and

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Spin-split bands cause the indirect band gap of $(CH_3NH_3)PbI_3$: Experimental evidence from circular photogalvanic effect

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Abstract

Long carrier lifetimes and diffusion lengths form the basis for the successful application of the organic-inorganic perovskite $(CH_3NH_3)PbI_3$ in solar cells and lasers. The mechanism behind the long carrier lifetimes is still not completely understood. Spin-split bands and a resulting indirect band gap have been proposed by theory. Using near band-gap left-handed and right- handed circularly polarized light we induce photocurrents of opposite directions in a single-crystal $(CH_3NH_3)PbI_3$ device at low temperature (4 K). The phenomenom is known as the circular photogalvanic effect and gives direct evidence for phototransport in spin-split bands. Simultaneous photoluminecence measurements show that the onset of the photocurrent is below the optical band gap. The results prove that an indirect band gap exists in $(CH_3NH_3)PbI_3$ with broken inversion symmetry as a result of spin-splittings in the band structure. This information is essential for understanding the photophysical properties of organic-inorganic perovskites and finding lead-free alternatives. Furthermore, the optically driven spin currents in $(CH_3NH_3)PbI_3$ make it a candidate material for spintronics applications.

The Optical Spectrum of Single-Crystal $(CH_3NH_3)PbBr_3$ Cleaved in Ultrahigh Vacuum

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To explore the intrinsic optical properties of $(CH_3NH_3)PbBr_3$, we measure temperature-dependent one-photon and two-photon induced photoluminescence from single crystals cleaved in ultrahigh vacuum. Comparison of the two allows to identify defect emission and to extract absorption spectra, when diffusion is taken into account. We find two optical transitions: a direct one at an energy of 2.31 eV independent of temperature, and an indirect one at 2.25 eV (2.22 eV) in the orthorhombic (tetragonal) phase. The spectra are consistent with Rashba-type spin-splittings in the band structure by 60 meV (90 meV). Each transition is accompanied by an excitonic transition ≈ 22 meV lower in energy. In the cubic phase, the binding energy of the exciton related to the direct transition is smaller. Excitonic emission associated with the indirect transition redshifts, possibly because of phononic effects. High-energy emission from free carriers is observed with higher intensity than reported in earlier studies. It disappears after exposure to air.

Organic-inorganic perovskite semiconductors (OIPS) have opened a whole new field in optoelectronics [1–7]. A comprehensive understanding of the underlying photophysics is still under development. Therefore, detailed knowledge is required of the band structure of OIPS [8–12], modifications by local disorder [13–18], excitonic effects [19–24], polaronic screening [25–28], and their interplay. Many studies that tackle these questions rely on the interpretation of (time-resolved) optical spectroscopy. Experimental data and their interpretation, however, show strong variations. Spectroscopic results obtained from thin films depend on growth technique [29–33], grain size [30, 34], and environmental conditions [35, 36].

For example, exciton binding energies between 15 and 84 meV [23, 37–42] have been reported for $(CH_3NH_3)PbBr_3$. A recent study on lead-bromide single-crystals found photoluminescence (PL) from high-energy carriers [28] with the potential to enhance solar cell performance, possibly beyond the Shockley-Queisser limit [43]. High-energy carriers have not been apparent to the same degree in earlier studies on thin films. Polaron formation involving reorientation of the organic molecules was proposed as the mechanism that suppresses electron-phonon scattering [28]. A recent study found a double peak structure with a peak spacing of 60 meV in the PL spectrum of $CH_3NH_3PbI_3$ [44]. From pressure-dependent experiments the authors identified direct and indirect optical transitions in the presence of Rashba-type spin-splitting as the origin of the two peaks. Rashba-type spin splitting has been predicted for $CH_3NH_3PbBr_3$ as well [8, 29, 45, 46], and we recently confirmed it experimentally using surface-sensitive photoelectron spectroscopy [47]. In PL from $CH_3NH_3PbBr_3$, a similar double-peak structure is thus expected as in case of $CH_3NH_3PbI_3$. Previously, two PL peaks at 2.22 eV and 2.3 eV were attributed to phases with lower and higher band gap in the bulk and surface-near region of $CH_3NH_3PbBr_3$ [48]. Yet, measurements in the surface-near region of OIPS are particularly challenging, since the crystals are extremely sensitive to environmental gas adsorption [35].

To access intrinsic material properties, we perform steady-state PL spectroscopy at low excitation density on surfaces of $(CH_3NH_3)PbBr_3$ single crystals cleaved in ultrahigh vacuum (UHV). These surfaces emit broadband PL light. We also measure bulk-sensitive steady-state PL spectra induced by two-photon absorption (TPI-PL). Because of the vastly different excitation depths, absorption spectra can be extracted from the combination of PL and TPI-PL when diffusion is taken into account. The procedure poses a viable route to extend temperature-dependent optical absorption spectroscopy to single crystals. We find a prominent direct transition at a photon energy of 2.31 eV, and an indirect transition slightly lower in energy. The transitions can be assigned to Rashba-type spin-split bands. Their spacing increases from 60 meV to 90 meV as $(CH_3NH_3)PbBr_3$ undergoes its phase transition from the orthorhombic to the tetragonal structure at 150 K. Each transition is accompanied by an exciton with a binding energy of ≈ 22 meV at temperatures ≤ 200 K. In the high-temperature cubic phase, the binding energies of the two excitons show opposite trends. In addition, we observe intense high-energy PL

Strain-Modulated Charge Transport in Flexible PbS Nanocrystal Field-Effect Transistors

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Extensive progresses in understanding charge carrier transport in semiconducting colloidal nanocrystals (NCs) have provided hope to exploit this class of materials for low-temperature processed electronic and optoelectronic devices. Among many types of NCs, lead chalcogenide (PbX; X = S, Se, Te) systems are the most promising because they have large Bohr exciton radius leading to strong quantum confinement, thus high absorbance, and at the same time they allow easy synthetic control of size and shape.[1–6] In solution, these NCs are coated with long-alkyl chain ligands, which maintain their structural properties as well as give them solubility in most organic solvents. Once deposited into solid films, these long ligands need to be replaced with shorter ones to strengthen electronic coupling as well as allow tunneling of charge carriers between nanocrystals, thus improving film conductivity. Importantly, this ligand exchange can be easily done either in solution phase or in solid phase, both techniques are compatible with solution processable fabrication methods such as spin-coating, dip-coating, ink-jet printing, etc.[7–12] This solution processability, combined with low temperature processing, opens up opportunities to use this material to fabricate electronic and optoelectronic devices on flexible plastic substrates.[13,14]

As the active materials are deposited onto flexible substrates, bending, folding, or stretching of the substrate is able to induce mechanical strain on the active layer which influences the characteristics of the fabricated devices. Recently, mechanical strain effects have been intensively investigated on organic semiconductor thin film transistors (TFTs).[15–17] The application of compressive strain on pentacene films has allowed improving the film conductivity and carrier mobility in TFT devices as a consequence of reduced molecular spacing. Oppositely, applied strain produces increased spacing which leads to the decrease in the carrier mobility.[16–19] The effect of mechanical strain on lead chalcogenide NC devices, particularly in TFTs, is still poorly investigated. As the bulk moduli of organic ligands has been reported to be lower than the NC cores, the introduction of mechanical strain is expected to have a great impact on the properties of the fabricated devices, with the potential to improve charge mobility in this system.[1,20] Therefore, the effect of mechanical strain on the electrical properties of NC-TFTs needs to be addressed to further understand their physical properties as well as to strengthen the applicability of NCs for diverse applications.

Here, we report a study of the effect of mechanical strain on the electrical characteristics of PbS field-effect transistors (FETs). As a gate dielectric, we use ion gel, which is able to accumulate high carrier concentration leading to electron mobility as high as 2.1 $cm^2 V^{-1} s^{-1}$. Upon the application of compressive strain, we observe improvement in the source–drain current, which leads to an increase in the electron mobility up to 45% at 2% strain. This improvement is associated to the reduced barrier length between NCs due to the bending of the crosslinking ligands. In the opposite strain direction, we observe reduction in the electron mobility which is an indication of the increase of the NC distance. Interestingly, we find that the change in the electron mobility is followed by the variation in the threshold voltages of the devices depending on the direction of the strain. The decreased threshold voltages as the compressive strain is applied can be attributed to the increase of the transfer integral between the NC arrays, which results in a more efficient trap filling, thus reducing carrier trapping. Meanwhile, the increased carrier traps can be responsible for the increase of the threshold voltages with the application of tensile strain. Furthermore, the observed larger effect during the application of

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Enabling Ambipolar to Heavy n-Type Transport in PbS Quantum Dot Solids through Doping with Organic Molecules

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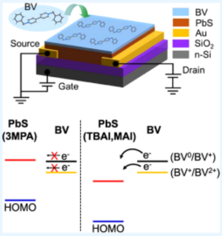
Supporting Information

ABSTRACT: PbS quantum dots (QDs) are remarkable semiconducting materials, which are compatible with low-cost solution-processed electronic device fabrication. Understanding the doping of these materials is one of the great research interests, as it is a necessary step to improve the device performance as well as to enhance the applicability of this system for diverse optoelectronic applications. Here, we report the efficient doping of the PbS QD films with the use of solution-processable organic molecules. By engineering the energy levels of the donor molecules and the PbS QDs through the use of different cross-linking ligands, we are able to control the characteristics of PbS field-effect transistors (FETs) from ambipolar to strongly n-type. Because the doping promotes trap filling, the charge carrier mobility is improved up to 0.64 cm^2 V^{-1} s^{-1}, which is the highest mobility reported for low-temperature processed PbS FETs employing SiO$_2$ as the gate dielectric. The doping also reduces the contact resistance of the devices, which can also explain the origin of the increased mobility.



KEYWORDS: *quantum dots, benzyl viologen, doping, ligands, field-effect transistors*

INTRODUCTION

PbS colloidal quantum dots (QDs) have been shown to be promising as semiconducting building blocks for optoelectronic devices, such as solar cells,[1−7] photodetectors,[8−11] and light-emitting devices.[12−14] This class of materials makes it possible to fabricate electronic devices using solution-processable methods such as blade-coating, dip-coating, printing, and roll-to-roll processes.[15−20] Recently, many efforts have been devoted to exploit PbS QDs as active materials for field-effect transistors (FETs).[17,18,21,22] The fabrication of FETs offers the possibility to integrate them in more advanced electronic devices, such as complementary metal oxide semiconductor-like inverters, integrated logic circuits, radio frequency identification systems, etc.[23,24] Their use in FETs, however, is still challenging because they suffer from low charge carrier mobility due to the high number of carrier traps on their surface. Therefore, improving the charge carrier mobility in FETs based on PbS QDs is crucial to enhance their potential for diverse applications.

Doping is an effective tool to improve the charge carrier mobility in semiconductors.[24−27] Although PbS QDs are n-type on the basis of their stoichiometry,[5,22,28] many published studies show strategies to turn them into p-type.[29,30] The p-type doping is mainly achieved by exposing samples to air, which gives rise to a significant increase of the hole mobility and density in the films.[29,30] A better control was achieved by evaporation of sulfur and selenium, or acting on the surface of the QDs with specific ligands.[5,22,31] On the other hand, studies on heavy n-type doping of the PbS QD films are still limited. The energy offset often built at the interface of semiconductor and dopant is responsible for inefficient electron transfer from the highest occupied molecular orbital (HOMO) of the dopant to the lowest unoccupied molecular orbital (LUMO) of the semiconductor.[32] Recently, benzyl viologen (BV) has been reported as a promising n-type dopant for the carbon nanotubes and MoS$_2$ systems.[26,33] Due to its shallow HOMO level, BV molecule treatment induces carrier doping in samples which favors electron transfer to the semiconducting films. To date, the use of BV as an n-type dopant in PbS QD films has not been investigated yet. This leaves a question on the possibility to use BV for obtaining strong n-type doping of the

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Broadening of Distribution of Trap States in PbS Quantum Dot Field-Effect Transistors with High-*k* Dielectrics

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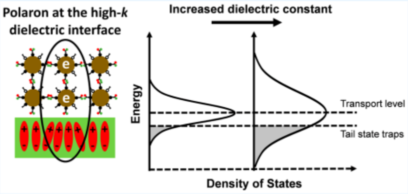
Supporting Information

ABSTRACT: We perform a quantitative analysis of the trap density of states (trap DOS) in PbS quantum dot field-effect transistors (QD-FETs), which utilize several polymer gate insulators with a wide range of dielectric constants. With increasing gate dielectric constant, we observe increasing trap DOS close to the lowest unoccupied molecular orbital (LUMO) of the QDs. In addition, this increase is also consistently followed by broadening of the trap DOS. We rationalize that the increase and broadening of the spectral trap distribution originate from dipolar disorder as well as polaronic interactions, which are appearing at strong dielectric polarization. Interestingly, the increased polaron-induced traps do not show any negative effect on the charge carrier mobility in our QD devices at the highest applied gate voltage, giving the possibility to fabricate efficient low-voltage QD devices without suppressing carrier transport.



KEYWORDS: *field-effect transistors, high-k, PbS quantum dots, polaron, trap states*

INTRODUCTION

Lead sulfide quantum dots (PbS QDs) have been demonstrated in recent years to be interesting semiconducting building blocks for the fabrication of solution-processable field-effect transistors (FETs) and other optoelectronic devices.[1−8] PbS QDs are dispersed in solution, as they are capped with long-alkyl chain ligands, which provide good solubility in most organic solvents.[9−11] Because of this solution processability, fabrication of QD-FETs is compatible with low-cost deposition technology such as blade-coating, dip-coating, roll-to-roll and inkjet printing.[1,3,12−14] As they are interfacial devices, in FETs the nature of the semiconductor/insulator interface is crucial: it influences the performance as well as the properties of the fabricated devices.[2,10,13−17] When SiO_2 is used as dielectric, dangling bonds due to hydroxyl (OH) groups on the dielectric surfaces act as carrier traps, which limit the performance of devices.[2,13,16,18−22] Moreover, SiO_2 gating in FET devices suffers from very high operating voltage due to its low capacitance, which is not compatible with practical applications.

Reducing the operating voltage of FETs is a necessary step to use them for a broader range of applications. A lower operating voltage can be achieved with the use of gate insulators with high dielectric constant (high-*k*).[13,23−27] In organic semiconductor FETs, however, energetic disorder and polaron relaxation are enhanced at the semiconductor/insulator interface when high-*k* insulators ($k > 3$) are utilized.[28−30] This disorder and polaronic-related interaction may modify the electronic structure, such as the nature of trap states, at the semiconductor/insulator interface and are responsible for the reduced charge carrier mobility in some reported high-*k* gated organic FETs.[28,31] While localized (trap) states with the use of high-*k* dielectrics have been intensively studied in organic FETs, little information is available for FETs based on PbS QDs. Since the trap states can strongly determine the performance of QD-FET devices, and at the same time dielectrics with higher *k* are

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Introducing a New Potential Figure of Merit for Evaluating Microstructure Stability in Photovoltaic Polymer-Fullerene Blends

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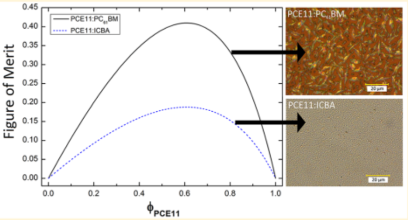
Supporting Information



ABSTRACT: A theoretical understanding of the microstructure of organic semiconducting polymers and blends is vital to further advance the optoelectronic device performance of organic electronics. We outline the theoretical framework of a combined numerical approach based on polymeric solution theory to study the microstructure of polymer:small molecule blends. We feed the results of ab initio density functional theory quantum chemistry calculations into an artificial neural network for the determination of solubility parameters. These solubility parameters are used to calculate Flory−Huggings intermolecular parameters. We further show that the theoretical values are in line with experimentally determined data. On the basis of the Flory−Huggings parameters, we establish a figure of merit as a relative metric for assessing the phase diagrams of organic semiconducting blends in thin films. This is demonstrated for polymer:fullerene blend films on the basis of the prototypical polymers poly(3-hexylthiophene-2,5-diyl) (P3HT) and poly[(5,6-difluoro-2,1,3-benzothiadiazol-4,7-diyl)-*alt*-(3,3-di(2-octyldodecyl)-2,2,5,2;5,2-quaterthiophen-5,5-diyl)] (PffBT4T-2OD). After confirming the applicability of our model with a broader range of materials and differences in molecular weight, we suggest that this combined model should be able to inform design criteria and processing guidelines for existing and new high performance semiconducting blends for organic electronics applications with ideal and stable solid state morphology.

INTRODUCTION

A fundamental understanding of the thermodynamics that governs the complex nanostructural properties of organic semiconductors is of utmost relevance for both basic science and technological applications. For instance, thermodynamic driving forces determine such important processes as film formation, drying, and crystallization, thereby controlling the optoelectronic properties of the semiconductor. In the case of photovoltaic polymer blends, the thermodynamics of mixing may determine the evolution of the local morphology and, consequently, alter the charge-transport behavior as well as the light-harvesting capabilities and overall performance lifetime of the final device.[1,2] Notably, the efficiency of the bulk heterojunction (BHJ) architecture in organic solar cells relies on the spontaneous organization energy (free energy) that forces the active layer into (in the simplest case) bicontinuous donor rich and acceptor rich regions mixed on a sufficiently fine length scale.[3] This microstructure evolution into phases has been proposed as being essential to the understanding of optimum organic photovoltaic (OPV) performance.[4,5] As such, the miscibility of the donor and acceptor materials, the size and composition of the phase-separated domains, their crystalline character, the formation of percolating charge transport networks, and the vertical concentration gradient are all important factors that must be considered experimentally and theoretically for establishing guidelines toward ideal photovoltaic blends. In this context, the development of a predictive model for morphology formation is a long-lasting endeavor. Its realization would represent a powerful toolbox in the quest for highly efficient and stable device performance.

While an important framework has emerged in recent years in an attempt to draw a critical link between molecular

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Nanoscale Morphology of Doctor Bladed versus Spin-Coated Organic Photovoltaic Films

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Recent advances in efficiency of organic photovoltaics are driven by judicious selection of processing conditions that result in a "desired" morphology. An important theme of morphology research is quantifying the effect of processing conditions on morphology and relating it to device efficiency. State-of-the-art morphology quantification methods provide film-averaged or 2D-projected features that only indirectly correlate with performance, making causal reasoning nontrivial. Accessing the 3D distribution of material, however, provides a means of directly mapping processing to performance. In this paper, two recently developed techniques are integrated—reconstruction of 3D morphology and subsequent conversion into intuitive morphology descriptors —to comprehensively image and quantify morphology. These techniques are applied on films generated by doctor blading and spin coating, additionally investigating the effect of thermal annealing. It is found that morphology of all samples exhibits very high connectivity to electrodes. Not surprisingly, thermal annealing consistently increases the average domain size in the samples, aiding exciton generation. Furthermore, annealing also improves the balance of interfaces, enhancing exciton dissociation. A comparison of morphology descriptors impacting each stage of photophysics (exciton generation, dissociation, and charge transport) reveals that spin-annealed sample exhibits superior morphology-based performance indicators. This suggests substantial room for improvement of blade-based methods (process optimization) for morphology tuning to enhance performance of large area devices.

1. Introduction

Research into photovoltaic (PV) devices composed of organic materials (organic PV or OPV) have been a recent hot topic because organic materials can be deposited from solution over large areas, which promised to greatly reduce the cost of PV device fabrication.[1,2] In addition, to reduced fabrication cost, OPV layers can be coated onto substrates with nontraditional form factors for building integrated applications.[3–5] Potential advances in flexible transparent substrates also open the possibility of extremely light weight or flexible devices.[6–9] Recent validated device efficiency records of over 10% demonstrate that OPV devices can be fabricated with high power conversion efficiency.[10–15] Also, OPVs have recently been demonstrated to be more efficient than crystalline Si under indoor lighting, opening a niche application for OPV that will require consistent manufacturing.[16] However, it has also been demonstrated that group-to-group consistency is low for the solution-fabricated devices in large part, because small differences in fabrication technique can lead to large differences in device performance.[17] These differences come about because OPV active layers are mixtures of donor polymers with small-molecule acceptors that self-assemble and phase separate during the film-drying process. As a result, the length scale for phase separation and the purity of the domains are a complex product of the donor/acceptor miscibility, solubilities of the donor and acceptor, surface energies of the donor, acceptor, and substrate, drying rate, and postdrying thermal treatments.[18,19]

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Experimental efficiency of a low concentrating CPC PVT flat plate collector

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Solar thermal
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Fluid
Concentration
Flat plate
Experimental

ABSTRACT

PVT collectors aim to solar co-generation of electricity and heat. An new concept raises thermal efficiency by concentrating sunlight with CPC reflectors, in order to access a higher number of solar thermal applications. Losses in PV efficiency due to a higher operating temperature are accepted with regard to a higher overall collector efficiency. As a side effect, the concentration lowers the material usage of PV and enables a high efficient thermal coupling of the PV cell to the heat carrying fluid.

The work focuses on the construction, as well as on the angle dependent electrical and thermal measurement of the real-size CPC PVT collector prototype (1460 mm × 600 mm × 150 mm). In previous publications, calculations and experiments studied the influence of the CPC reflectors on the PV efficiency. Further, the thermal coupling between PV cell and heat carrier fluid has been measured in a lab experiment. These results, together with transient annual simulations, were considered in the design process of the CPC PVT prototype with an angular acceptance range of ±25°.

The experiments were conducted on the outdoor solar test facility at ZAE Bayern in Garching, Germany. The thermal and PV efficiency has been measured with MPP tracking, as well as for open circuit voltage for fluid temperatures up to 107 °C.

It could be shown, that the thermal efficiency while MPP tracking is elevated to 34% compared to a glazed flat plate PVT with 17% for collector temperatures 60 K over ambiance. At the same time, the electrical efficiency drops from 15% cell efficiency to an overall collector efficiency of 9%, due to the optical setup, temperature effects and a non-uniform flux distribution caused by the reflectors.

1. ***Introduction:***

1.1. State of the art

As in the field of solar thermal collectors, a variety of PVT collector types exist, differing in their thermal efficiency or the heat carrier medium. Much research on non-concentrating PVT collectors has been done: For an overview see Avezov et al. (2011), Zhang et al. (2011), Zondag (2008), Charalambous et al. (2007) and Ibrahim et al. (2011). Aste et al. (2014) treat especially water flat plate PVT collectors. Further, in 2005, PVT Roadmap (2005) was released within the 6th framework program of the EU.

As a PVT absorber does not have the optical and thermal properties of a selective coating in a conventional solar thermal collector, the thermal efficiency of a PVT collector is lower. In order to improve thermal efficiency, there are in principle three ways to decrease thermal losses:

First of all, a glazed front side cover and a backside thermal insulation can be applied to the PVT absorber unit, similar to a solar thermal flat plate collector. This is for example shown by Dupeyrat et al. (2011) and Pierrick et al. (2015).

In order to diminish convective transfer inside the collector, one can evacuate the inside (see Stryi-Hipp et al., 2014) or use fill (noble) gases, as proposed by Antonanzas et al. (2015).

Another way would be to suppress thermal losses due to heat radiation. To compensate a rather high emissivity of the PVT absorber, low-e coatings on either the PVT absorber or the inside of the covering glass can be applied (Laemmle et al., 2016a,b).

The method used for the presented collector concept is the reduction of heat emitting absorber surface by solar concentration. This can be done with a linear concentrating parabolic concentrator, like shown by Bernardo et al. (2011) and Coventry (2005), or with CPC reflectors. While linear concentrating parabolic

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Revealing Minor Electrical Losses in the Interconnecting Layers of Organic Tandem Solar Cells

Mario Prosa, Ning Li,* Nicola Gasparini, Margherita Bolognesi, Mirko Seri, Michele Muccini, and Christoph J. Brabec*

The interconnection layer (ICL) of organic multijunction solar cells represents one of the most delicate parts to ensure an efficient device operation. In view of pushing the efficiencies toward the theoretical limit, the individuation of minor losses affecting the ICL operation is of crucial importance. However, the difficulties arising from its position within the complex device structure typically hamper an accurate and selective investigation of the ICL. Here, a method based on the analysis of the photo-generated current density–voltage (J_{ph}–V) response of solar cells, in the region of bias over the open-circuit voltage, is proved to individuate minor electrical losses within the ICL. Interestingly, the proposed method is demonstrated to effectively operate on tandem substructures, where different ICLs are investigated through the combination of materials having diverse characteristics. Furthermore, the use of a complementary investigation technique based on electroluminescence (EL) analysis allows to distinguish the specific nature of the electrical losses. The combination of J_{ph}–V and EL analyses represents an elegant and advanced approach to shed light on the quality of ICLs in tandem substructures by avoiding the fabrication of the more complex tandem architecture.

Through the progressive improvements over the years, organic photovoltaics (OPVs) resulted as one of the most attractive candidates for the deployment of sustainable energy. The exponential evolution of this technology occurred through relevant breakthroughs in terms of device efficiency and stability that,[1–4] in conjunction with the remarkable merits and fascinating functional characteristics typical of organic materials,[5,6] place OPVs among the most promising prospective solar technologies.[7]

To date, single-junction organic solar cells (OSCs) have reached power conversion efficiencies (PCEs) surpassing 13%,[8] however further improvements are still expected. The most significant limitation arises from the energy mismatch between the incident solar photons and the bandgap of organic semiconductors.[9]

To circumvent this problem, an effective approach is to divide the solar cell into subcells (the multijunction concept) where each active layer absorbs photons of a limited interval of energies and transmits the rest to the other subcells. In this kind of device architecture, the subcells are monolithically stacked in a single device and electrically connected, usually in series, by an interconnecting layer (ICL) consisting of an electron and a hole transporting layer (ETL and HTL, respectively).

Following this approach, PCEs up to 21% were predicted for double-junction (tandem) OSCs,[10] which is higher than the 15% estimated for single-junction devices.[11] However, despite the great expectations, the efficiency of series-connected tandem solar cells is still below the predicted value (current best PCE: 13.8%).[12] One of the most critical issues of the tandem architecture is represented by the ICL. Indeed, it should simultaneously fulfill a multitude of electrical, optical, and mechanical requirements to ensure an effective device operation.[13] Despite a consistent amount of studies focused on the ICLs of multijunction solar cells, a clear picture of the processes involved during its operation is still lacking.[14–17] This demonstrates the need of a deeper understanding of the physics of the system, which would be beneficial both in terms of device processing and efficiency.

The main difficulties to study the ICL arise from its position and role within the tandem architecture, which hamper a selective investigation by neglecting the contributions from the rest of the device. A possible approach to selectively study the ICL is through an electrical contact with an external output, i.e., using a three terminal connection.[18] Despite this method offers the great advantage to specifically investigate the ICL during real operation, it requires the introduction of an additional

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Carbon Photodetectors: The Versatility of Carbon Allotropes

Moses Richter, Thomas Heumüller, Gebhard J. Matt, Wolfgang Heiss, and Christoph J. Brabec**

We dedicate this review to Prof. Dr. Nazario Martín on the occasion of his 60th birthday.

Carbon-based organic electronics are a technology, with the potential of complementing and substituting opto-electronic devices based on inorganic semiconductors and metals. In the group of organic semiconductors, carbon allotropes come with outstanding opto-electric properties and are remarkable candidates for novel applications like printed electronics via solution-processing on mechanically flexible, robust and light weight substrates, while reducing the environmental impact. Carbon allotropes like fullerenes, graphene quantum dots (GQD), carbon nanotubes (CNT), graphene and also diamond are especially interesting for photodetectors due to their tunable bandgap, high absorption coefficients and high charge carrier mobilites. These unique opto-electric properties of the allotropes, which strongly depend on their molecular dimensionality (0D, 1D, 2D and 3D), allow each allotrope to be used in a preferential range. Hence, relying on the intrinsic properties of carbon allotropes or by hybridization, carbon-based photodetectors are built for a spectral bandwidth, reaching from gamma-rays to THz radiation. This review highlights the recent advances in photodetectors based on fullerenes, GQDs, CNTs, graphene and diamond, with the focus on room temperature-operated devices. The versatility of multi-dimensional carbon allotropes is outstanding, and promising results outline the maturing of all carbon-based photodetection across the technologically relevant wavelengths.

1. Introduction

The conversion of light, which is electromagnetic radiation that carries energy and can be defined by a wavelength or frequency, became essential to the technological age. In modern societies, it is impossible not to encounter at least one photodetecting device or component on a daily basis. Currently, the photovoltaic technology is making a big impact by reallocating the electric power, which mankind consumes in the 21st century, to a more sustainable and environmental friendly technology. For solar cells, the power conversion efficiency of sun light is of importance and benefits from a broad optical absorption and a high photocurrent and photovoltage.[1] On the other hand, photodetectors are employed with the primary goal of delivering a precise electrical signal, photocurrent or photovoltage, most representative for the detected illumination event. Thereby, they serve as interface between optical information and electronic circuitries. Hence, photodetectors find nowadays application in consumer electronics (digital imaging, contactless thermometers, self-driving cars) medical care, environmental monitoring, industrial automation, digital communication, quality control, security and astronomy.

For an optimal performance, the spectral sensitivity and response speed of photodetectors are chosen to meet the demands and can be tailored over several orders of magnitude by adopting the material and device architecture. Two detector types can be distinguished. i) Photonic detectors (e.g., photoconductors, photodiodes, phototransistors) rely on the direct conversion of absorbed photons to charge carriers, whereas ii) thermal detectors rather exploit electrical changes upon a temperature change in the absorber material. Ultimately, the light matter interaction inside the detector must lead to the generation of an electric signal and depends on the photon energy E_{ph} and wavelength λ, respectively. For high energy photons, gamma rays ($E_{ph} > 100$ keV, $\lambda < 12$ pm) and X-rays ($E_{ph} > 1$ keV, $\lambda < 1$ nm), effects like the photoelectric effect, Compton scattering or pair production determine the electric response and increase with the atomic weight of the photoactive material utilized in the detector. Commonly used for direct X-ray detectors are photoconductors like amorphous selenium (a-Se) or cadmium telluride (CdTe).[2,3] For photodetection of longer wavelength and smaller photon energies, semiconductors are suitable, as the photoresponse is rather based on electron-hole pair generation by optical excitation across the bandgap. Preferred detector materials for ultraviolet (UV) light, which is defined

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Automated synthesis of quantum dot nanocrystals by hot injection: Mixing induced self-focusing

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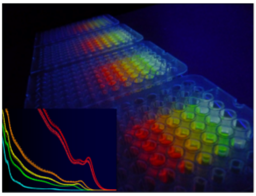
HIGHLIGHTS

- Successful automation of the hot injection synthesis of cadmium selenide as challenging model system.
- Implementation of high-throughput experimentation for nanocrystal synthesis.
- High reproducibility of produced samples with some having nearly identical numbers of building blocks.
- Observation of mixing-induced focusing/defocusing.
- Unique insight to process-structure relationships during quantum dot synthesis.

GRAPHICAL ABSTRACT



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ABSTRACT

The hot injection technique for the synthesis of quantum dots (QDs) is a well-established and widely used method in the lab. However, scale-up rules do not exist. One reason is that in particular the role of process parameters like mixing on particle formation is largely unknown, as systematic examination of the latter is impossible for the laborious and complex manual synthesis. Herein we studied the mixing induced self-focusing of particle size distributions (PSDs) of CdSe QDs using automation in combination with a defined stirrer geometry. Basis for our study is a platform that allows parallelization with inline temperature monitoring, defined injection rate, accurate sampling times as well as controlled stirring. Reproducibility in terms of optical product properties was analyzed by absorption and emission whereas reproducibility in terms of the PSD was verified by deconvolution of UV/Vis absorbance spectra and especially by analytical ultracentrifugation (AUC) complemented by transmission electron microscopy (TEM). In line with previous results, AUC confirmed that even QDs made by hot injection in an automated setup are polydisperse with multimodal size distributions. Finally, reproducibility in combination with early stage sampling and controlled mixing allowed us for the first time to analyze the influence of stirring on focusing and defocusing of PSDs, that has been expressed in terms of the evolution of the relative standard deviation (RSD). Our work paves the way to gain in-depth understanding of often forgotten process-structure relationships of colloidal nanoparticles which eventually is a first step in the direction of the development of scalable synthesis and reliable application of high-quality QDs in technical applications.

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Suppressing photooxidation of conjugated polymers and their blends with fullerenes through nickel chelates†

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Conjugated polymer semiconductors offer unique advantages over conventional semiconductors but tend to suffer from electro-optic performance roll-off, mainly due to reduced photofastness. Here, we demonstrate that the commodity nickel chelate nickel(II) dibutyldithiocarbamate, $Ni(dtc)_2$, effectively inhibits photooxidation across a wide range of prototypical π-conjugated polymer semiconductors and blends. The addition of 2–10 wt% of $Ni(dtc)_2$ increases the resilience of otherwise quickly photobleaching semiconducting thin films, even in the presence of detrimental, radical forming processing additives. Using electron spin resonance spectroscopy and sensitive oxygen probes, we found that $Ni(dtc)_2$ acts as a broadband stabilizer that inhibits both the formation of reactive radicals and singlet oxygen. The mechanism of stabilization is of sacrificial nature, but contains non-sacrificial contributions in polymers where singlet oxygen is a key driver of photooxidation. Ultrafast pump–probe spectroscopy reveals quenching of triplet excited states as the central mechanism of non-sacrificial stabilization. When introduced into the active layer of organic photovoltaic devices, $Ni(dtc)_2$ retards the short circuit current loss in air without affecting the sensitive morphology of bulk heterojunctions and without major sacrifices in semiconductor properties. Antioxidants based on nickel complexes thus constitute functional stabilizers for elucidating degradation mechanisms in organic semiconductors and represent a cost-effective route toward organic electronic appliances with extended longevity.

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Broader context

Organic semiconductors based on conjugated polymers bear exceptional opportunities for many disruptive technologies, including light and power generation, sensor technology and electronic circuitry, which could potentially be realized in a sustainable fashion using highly efficient and low-cost approaches. However, conjugated polymers suffer from photo-oxidation-induced performance loss and need to be carefully encapsulated, compromising both applicability and cost benefits. In the present work, we introduce a nickel chelate, nickel(II) dibutyldithiocarbamate, as a universal antioxidant for increasing the longevity of conjugated polymers. We carried out a mechanistic study that quantitatively describes the stabilization of conjugated polymer moieties with technological relevance for OLEDs, OPVs and OFETs. We introduce for the first time a figure of merit (FOM) as a stabilization metric for antioxidants in conjugated polymers. This FOM serves likewise to distinguish between sacrificial and non-sacrificial protective mechanisms. We draw wide ranging conclusions that reflect on how conjugated polymer and polymer:fullerene blends photo-oxidize and how the underlying mechanisms can be significantly suppressed in the presence of nickel chelates. Finally, we demonstrate its beneficial use in a broad range of organic photovoltaic devices.

Introduction

Organic semiconductors have been envisioned for many disruptive technologies but have a tendency to undergo deterioration of functional properties in the presence of light and oxygen.[1–5] This translates into the need for careful encapsulation strategies, compromising both applicability and cost benefits.[6] Conceptually new strategies are necessary to suppress degradation reactions. In the plastic and rubber industry, stabilizing additives are an

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Solubility and dissolution kinetics of GaN in supercritical ammonia in presence of ammonoacidic and ammonobasic mineralizers

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ABSTRACT

Solubility and dissolution kinetics of GaN are investigated, as they represent essential parameters for ammonothermal crystal growth of GaN. *In situ* X-ray imaging is applied to monitor the dissolving crystal. Both ammonoacidic and ammonobasic conditions are investigated. Compared to NH_4F, the dissolution is generally much slower using NaN_3 mineralizer, leading to a much longer time needed to establish a saturated solution. The solubility of GaN at 540 °C and 260 MPa in supercritical ammonia with a molar concentration of NaN_3 of 0.72 mmol/ml is determined to be 0.15 ± 0.01 mol%. This suggest a severe refinement of raw gravimetric literature data also for alkali metal based mineralizers, as we reported previously for ammonium halide mineralizers. The order of magnitude is in good agreement with refined gravimetric solubility data (Griffiths et al., 2016). The apparent discrepancy between the literature and this work regarding the temperature range in which retrograde solubility occurs is discussed. A possible reason for the occurrence of retrograde solubility at high temperatures is described. The paper is complemented by a section pointing out and partially quantifying potential, reactor-material-dependent sources of errors.

1. Introduction

Ammonothermal crystal growth of GaN is a promising approach for the production of native GaN substrates on an industrial scale [1]. Native GaN substrates allow for the further improvement of performance and lifetime of GaN-based optoelectronic and electronic devices [2]. The ammonothermal crystal growth method is based on the dissolution of GaN in the temperature zone with higher GaN solubility and seeded growth from the supersaturated solution in the lower solubility zone [2], thus, the solubility of GaN is very important for both scientific understanding and technological optimization of the process. Furthermore, knowing how the solubility of GaN changes with temperature and pressure is expected to contribute to understanding the chemical and physical mechanisms governing dissolution. In the long run, identifying the underlying chemo-physical processes may allow for optimizing the selectivity of the mineralizer to maximize the normalized solubility of the nitride while minimizing the solubility of the reactor materials. Comparable attempts have been made using other supercritical fluids (e.g. CO_2) for which the deviating dependency of the solubility of different solutes on pressure and temperature is comparably well understood [3].

Despite the importance of knowing and tuning the solubility, literature data are both scarce and scatter in the order of magnitude range [4–9]. We have previously reported a novel method for investigating the solubility using *in situ* X-ray imaging [4]. In this work, more comprehensive information on the dissolution of GaN in presence of ammonium fluoride (NH_4F) and sodium azide (NaN_3) mineralizers will be presented. Information on the kinetics of dissolution and saturation of the solution will be given. The obtained solubility data will be discussed with respect to literature. In addition, potentially remaining sources of errors are analyzed semi-quantitatively.

2. Experimental

Regarding the autoclave and the X-ray imaging equipment, the experimental setup was almost identical to the one used in our previous study [4]. However, a few changes to the setup and experimental procedure were made as described in the following. Ammonia was purified using a gas purifier (MicroTorr MC190-702F) and no

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Characterization of protrusions and stacking faults in 3C-SiC grown by sublimation epitaxy using 3C-SiC-on-Si seeding layers

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Abstract

In this article, sublimation growth of 3C-SiC on 3C-SiC-on-Si seeding layers was evaluated by characterizing the densities of protrusions and stacking faults (SF). Both defects are among the most critical concerning the growth process and the realization of high quality material for device applications. By variation of growth parameters like temperature, growth rate and 3C-SiC-thickness we conducted a series of experiments and characterized these layers by optical microscopy and KOH etching. The protrusion density is predetermined by the seeding layers and was kept at a constant level, whereas a decrease of SF-density was observed with increasing layer thickness during subsequent sublimation growth steps. Therefore, in the case of Sublimation Epitaxy (SE) it has been found appropriate to distinguish between defects that can be reduced during SE and defects that are merely reproduced from the seeding material during sublimation growth. Furthermore, a weak trend towards a decrease of SF-density with increasing growth temperature was observed. The findings in this work demonstrates the potential of SE in growing thick and high-quality 3C-SiC layers if sufficiently good seeding layers were available. Copyright © 2017 VBRI Press.

Keywords: 3C-SiC, sublimation epitaxy, single crystalline, protrusions, stacking faults.

Introduction

Cubic silicon carbide (3C-SiC) is supposed to be a promising candidate for power electronics in the medium voltage range between 600 V and 1200 V [**1, 2**] that could fill the gap between silicon- and 4H-SiC-based applications. 3C-SiC shows the highest electron mobility and saturation drift velocity [**3, 4**] while the band gap (2.3 eV [5]) is the lowest among all SiC polytypes. In contrast to the situation for 4H- and 6H-SiC, trap states at the 3C-SiC/SiO$_2$-interface are within the conduction band representing a major advantage for MOS-devices [**1, 2**].

However, the cubic polytype of SiC shows various technological challenges regarding the growth-process and the lowering of defect-densities that hinder the implementation of reliable devices. Since Nishino et al. [**6**] introduced a multi-step Chemical Vapor Deposition (CVD) growth process for 3C-SiC heteroepitaxy on Si-substrates in 1982, a variety of approaches has been proposed aiming to improve the quality of cubic silicon carbide. Promising concepts include the growth on patterned Si-Substrates [**7–10**], the Switch-Back-Epitaxy [**11**] and the use of various precursors with varying C/Si ratios, just to mention a few of them.

From an economic point of few, heteroepitaxy on Si-substrates provides the greatest potential for cost reduction and scale up of wafer-size [**12**] and therefore outperforms epitaxy on hexagonal SiC-substrates. However, notwithstanding the promising results that have already been achieved with heteroepitaxy on Si, the 3C-SiC/Si-system still suffers from high defect densities. A large mismatch in lattice parameters (19.7 % at room temperature [**13, 14**]) and in thermal expansion coefficients (~ 23 % at deposition temperatures and 8 % at room temperature [**15, 16**]) between the two materials results in the incorporation of misfit dislocations [**17**], planar defects [**18**] and the occurrence of stress fields. The latter can even lead to a bending of the whole wafer, also referred to as “wafer-bow” [**19, 20**].

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Growing bulk-like 3C-SiC from seeding material produced by CVD

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We present a process to transfer CVD grown heteroepitaxial 3C-SiC on Si onto polycrystalline SiC, involving an etching step to get rid of the Si and a homogeneous carbon glue deposit, facilitating the resulting compound to be used as a seeding material for further growth process. In a sublimation sandwich setup, realized within an inductively heated physical vapor transport reactor, used for bulk growth of SiC, the thickness of the 3C-SiC seed was increased up to 850 µm while keeping the cubic polytype. With the introduction of Ta as a carbon getter, the gas phase composition is optimized in order to achieve an improved growth front. Single crystalline growth is confirmed by Laue diffraction and Raman measurements. The Raman peaks are shifted to higher wavenumbers, indicating compressive stress in the grown samples. Furthermore, a scale up of the process is demonstrated, showing the feasibility of growing 3C-SiC on an area of 10.5 cm^2 in a 2 inch setup featuring a thickness of approximately 570 µm.

1 Introduction For the application under harsh conditions, like high temperatures and chemically aggressive media, as well as high frequency and high power applications, Silicon Carbide (SiC) is the material of choice. The reasons for that are the high thermal conductivity and chemical inertness, in addition to the high disruptive strength and saturation drift speed [1].

The different SiC polytypes are determined by the stacking sequence of the Si-C double layers, leading to hexagonal, cubic, or rhombohedral crystal structures [2]. Despite the same stoichiometric composition, the different polytypes differ in their physical properties, for instance the band-gap ranging from 2.3 eV for 3C-SiC to 3.3 eV for 4H-SiC [1]. To date, wafers with diameters of up to 150 mm of the hexagonal 4H-SiC and 6H-SiC are commercially available. But for specific applications, as for example intermediate band solar cells [3] or MOSFETs [4], cubic 3C-SiC of high quality features promising properties. The bulk growth of the 3C polytype in a PVT-process is challenging due to its metastable nature and the lack of high quality 3C-SiC seeding-material.

In order to obtain high quality cubic SiC layers, the CVD heteroepitaxy on Silicon (Si) substrates has strongly advanced. However, the lattice mismatch ($a_{\mathrm{SiC}} = 0.436$ nm [5], $a_{\mathrm{Si}} = 0.543$ nm [6]) and the different thermal expansion coefficients [7], leading to structural defects and tensile strain in the 3C-SiC layer are still problematic. With increasing layer thickness the strain can be gradually reduced, but wafer bending gets more pronounced [8].

In this work, high quality seeding material produced by CVD heteroepitaxy is combined with a sublimation sandwich method, realized in a PVT setup used for bulk-growth of commercial SiC, in order to increase the 3C-SiC layer thickness over a large area.

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3C-SiC Bulk Sublimation Growth on CVD Hetero-Epitaxial Seeding Layers

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Keywords: cubic SiC, 3C-SiC, epitaxy, sublimation growth

Abstract. We report on the growth of bulk 3C-SiC by sublimation on epitaxial seeding layers (3C-SiC/Si) from chemical vapor deposition. We have reached a materials thickness of 0.85 mm and an area of 10.5 cm^2 which can be enlarged further. The high crystalline quality is characterized by the absence of secondary polytype inclusions and the absence double position grain boundaries.

Introduction

The cubic polytype of SiC shows technological challenges for the bulk-growth such as a high supersaturation, a silicon rich gas phase and a high vertical temperature gradient. A significant step for electronic devices, like MOSFETs and novel optoelectronic devices like intermediate band solar cells (theoretical $\eta \geq 60\%$), can be predicted for high quality material due to the high electron mobility and the wide bandgap. A number of approaches have been followed in the past with the goal to grow high quality cubic SiC for the application in electronic devices. Most attempts are carried out on seeding layers that have been prepared using hetero-epitaxy either on hexagonal SiC wafers or on cubic Si substrates [1-10]. The choice of (0001) SiC starting substrates has the advantage of perfect thermal match between the 3C-SiC layer and the underlying carrier. Due to the low stacking fault energy in SiC ((0001) plane in hexagonal SiC = (111) plane in cubic SiC), the maintenance of the cubic polytype is difficult and requires very stable step flow growth processing conditions on slightly off axis substrates [8,10]. The suppression of double position grain boundaries remains very critical. On the other hand, the application of (100) Si substrates provides 3C-SiC polytype stability once nucleation of 3C-SiC is accomplished. However, the significant mismatch of the thermal expansion coefficients of the Si-substrate and the hetero-epitaxially grown 3C-SiC using chemical vapor deposition (CVD) impose large internal stress and easily causes layer cracks. Although reasonable knowledge in the fundamentals of 3C-SiC growth has been achieved [1-10], large area, high quality cubic SiC feasible for electronic applications is hardly available so far.

In this study, we report on the sublimation growth of bulk 3C-SiC which has been performed on CVD hetero-epitaxial seeding layers (3C-SiC/Si). The work basis on significant progress of the preparation of thick and high quality 3C-SiC layers without double position grain boundaries [11] as well as on the provision of a defined and stable subsequent sublimation growth process [9][12]. The approximate material thickness and area so far are 0.85 mm and 10.5 cm^2, respectively, which legitimate the nomenclature "bulk" 3C-SiC.

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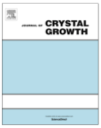

Sublimation growth of bulk 3C-SiC using 3C-SiC-on-Si (1 0 0) seeding layers

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ABSTRACT

We have developed a transfer process of 3C-SiC-on-Si (1 0 0) seeding layers grown by chemical vapor deposition onto a poly- or single-crystalline SiC carrier. Applying subsequent sublimation growth of SiC in [1 0 0] direction resulting in large area crystals (up to ≈11 cm^2) with a thickness of up to approximately 850 μm. Raman spectroscopy, Laue X-ray diffraction and electron-backscattering-diffraction revealed a high material quality in terms of single-crystallinity without secondary polytype inclusions, antiphase boundaries or double positioning grain boundaries. Defects in the bulk grown 3C-SiC, like protrusions with surrounding stressed areas, stem from the epitaxial seeding layer. The presented concept using 3C-SiC-on-Si seeding layers reveals a path for the growth of bulk 3C-SiC crystals.

1. Introduction

The technological advantages of silicon carbide in high temperature, high frequency and high power applications have advanced drastically since the start of its industrial production in the mid-90s. However, the growth of specific polytypes like cubic silicon carbide (3C-SiC) still poses problems to high quality and large diameter production. Growth conditions like a high supersaturation, a high temperature gradient, a silicon rich gas phase and the availability of seeding material for large area growth are difficult to establish simultaneously. Nevertheless, 3C-SiC features promising properties for devices like metal-oxide semiconductor field effect transistors (MOSFETs) exceeding the commercially available, hexagonal polytypes (6H and 4H) [1–3]. The heteroepitaxial approach growing 3C-SiC on Si using chemical vapor deposition (CVD) has been highly developed yielding large area (four to five inches diameter) and high quality material but a limited thickness due to wafer-bending caused by the lattice mismatch (a_{SiC} = 0.436 nm, a_{Si} = 0.543 nm [4]) which also results in cracks of the epi-layers [1]. Indeed, the quality of the grown 3C-SiC by CVD may be improved further with increased thickness [5,6]. For the growth of bulk or at least bulk-like 3C-SiC various approaches have been followed in recent years [7–19]. To date, no large area material with medium or low defect density that could be applied in state-of-the-art electronic device fabrication has been presented. Nevertheless, all studies so far have established the fundamentals for the successful growth of 3C-SiC bulk material [7–19]. The common difficulties to realize bulk 3C-SiC may be related to a challenging 3C-SiC nucleation and preservation of the 3C-SiC polytype throughout the growth process. Besides polytype changes and stacking faults (SFs), in particular double positioning grain boundaries (DPBs) and anti phase boundaries (APBs) in cubic SiC alters its crystalline quality and limits the technological application in electronic devices. Regarding SFs and APBs, the so called planar defects, a reduction or even an elimination using undulant, off-axis oriented Si substrates was already presented [20]. Merging the knowledge in literature [7–19], it is concluded by the authors of the current work that the growth of high quality cubic silicon carbide may be achieved by the application of high quality 3C-SiC template layers initially grown by CVD on (1 0 0) silicon followed by a physical vapor sublimation growth method.

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Tuning Electrical and Optical Properties of Transparent Conductive Thin Films Using ITO and ZnO Nanoparticles, Sol-Gel-ZnO and Ag Nanowires

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Abstract

The progress in the research on a wet-chemical or nanoparticle derived absorber layer for solar cells leads to the fabrication of a printable transparent front electrode. This eliminates the need for vacuum technology, when the vacuum chain is already breached for the absorber deposition. The objective of this work is the manufacturing and characterization of a vacuum-free, printable, transparent front electrode on the basis of conductive metal oxides like ITO and ZnO, while reducing Indium consumption and annealing temperature or duration. Nanoparticles as well as a sol-gel process were used to deposit transparent and conductive Aluminum Doped Zinc Oxide (AZO) thin films on glass substrates. Furthermore, the influence of ion-implantation-doping after layer deposition was examined. Different temperature treatments were applied after layer deposition or ion-implantation respectively to tune the conductivity of the thin films. For characterization of the thin-films four-point-probe measurements, white-light-interferometry, UV/VIS spectroscopy, and (FE) SEM were used. The sol-gel-layers achieved a conductivity of 314 S/cm whereas the nanoparticle derived ZnO layers only reached 1.15 - 20 S/cm. Finally, the application of silver nanowires resulted in a low sheet resistance of 5.8 Ω/□ which is even lower than for state-of-the-art sputtered AZO-layers (15 Ω/□) and allows low annealing temperatures of only 140 °C.

Keywords

Transparent conductive film, ITO & ZnO nanoparticles, Sol-Gel ZnO:(In,Al), Silver nanowires (Ag-NW)

Introduction

Transparent conductive oxides are widely used for a huge number of applications such as solar-cell window layers, electroluminescence lamps, touch screen displays and many more. The number one material used is ITO which has outstanding properties but relies on the scarce indium. Therefore, doped ZnO emerges more and more as an alternative to ITO. For CISe solar cells, sputtered ZnO window layers are commonly used. Since there is progress on solution processing of the absorber layer, the vacuum-chain is already interrupted for Chemical Bath Buffer Layer Deposition (CBD) and the scale-up of vacuum processing, necessary for large modules, is challenging, non-vacuum processes for ZnO deposition are interesting. Investigations have started since a long time in this field and are still performed recently [1-8], emphasizing low-temperature approaches and vacuum-free processing, or using silver nanowires or -particles for composite [9-11].

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High-performance direct conversion X-ray detectors based on sintered hybrid lead triiodide perovskite wafers

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Lead halide perovskite semiconductors are in general known to have an inherently high X-ray absorption cross-section and a significantly higher carrier mobility than any other low-temperature solution-processed semiconductor. So far, the processing of several-hundred-micrometres-thick high-quality crystalline perovskite films over a large area has been unresolved for efficient X-ray detection. In this Article, we present a mechanical sintering process to fabricate polycrystalline methyl ammonium lead triiodide perovskite ($MAPbI_3$) wafers with millimetre thickness and well-defined crystallinity. Benchmarking of the $MAPbI_3$ wafers against state-of-the-art CdTe detectors reveals competitive conversion efficiencies of 2,527 $\mu C\ Gy_{air}^{-1}\ cm^{-2}$ under 70 kV_p X-ray exposure. The high ambipolar mobility–lifetime product of $2 \times 10^{-4}\ cm^2\ V^{-1}$ is suggested to be responsible for this exceptionally high sensitivity. Our findings inform a new generation of highly efficient and low-cost X-ray detectors based on perovskite wafers.

Due to their outstanding physical properties, hybrid organic–inorganic perovskites (HOIP), and most notably $CH_3NH_3(Pb,Sn)(I,Br)_3$, have received extraordinary attention from the research community. Especially significant are the charge-transport properties of $MAPbI_3$, which has demonstrated long minority-carrier lifetimes and diffusion lengths that are comparable with single-crystalline covalent semiconductors[1–5].

A new application for this material class is the sensitive detection of high-energy radiation such as X-ray[6,7] and γ radiation[8]. The search for an ideal X-ray-sensitive photoconductor (PC) is of ongoing interest because most semiconductors with good charge-transport properties do not absorb high-energy radiation effectively. The latter, however, is an intrinsic property of HOIPs due to the presence of heavy metal and halide ions. Current state-of-the-art materials for direct X-ray detection[9] include stabilized amorphous Se (*a*-Se)[10], PbI_2 (ref. 11), HgI_2 (refs 12, 13), CdTe (ref. 14) and CdZnTe (ref. 15). *a*-Se detectors have been successfully commercialized but are limited to mammography applications due to their low absorption coefficient in the spectral regime higher than 50 keV. PbI_2 and HgI_2 detectors face stability issues that hinder their widespread application. Significant effort is being directed at Cd(Zn)Te (ref. 16), but upscaling to larger wafers and charge carrier trapping remain issues yet to be overcome.

Generally, for efficient X-ray absorption, the PC layer should be approximately three times larger than the attenuation length, which is the length at which 63% of photons are absorbed[17]. As discussed later in detail, HOIPs have attenuation lengths on the order of hundreds of micrometres for the X-ray energies commonly used in medical applications. Although the widely reported solution-process protocols for fabricating thin films of HOIPs are efficient in the sub-micrometre regime, producing several-hundred-micrometres-thick, high-quality films covering a large area is extremely difficult. In this Article, we present a room-temperature sintering process for $MAPbI_3$ microcrystals to form thick (200 μm to 1 mm) rigid wafers of virtually any size.

$MAPbI_3$ wafer sintering process

In contrast to covalent semiconductors such as Si and Cd(Zn)Te, which require high-temperature crystallization processes, ionic crystals can be processed from solution at low temperatures. An easily overlooked property of ionic crystals is their plasticity, which results in pressure-induced flow processes[18]. Although HOIPs are not pure ionic crystals, this material class does exhibit pressure-induced agglomeration effects.

The $MAPbI_3$ microcrystals presented here were synthesized by precipitation from a precursor solution at room temperature[19] (see Methods). The precipitated microcrystals were irregular in shape, with sizes ranging from 50 nm to 1 μm (Supplementary Fig. 1). By applying a pressure of 0.3 GPa to the microcrystals for 5 min using a hydraulic press, a compact $MAPbI_3$ layer (which will be referred to as a wafer) was formed. A series of wafers with 1/2 inch diameter and thickness ranging from 200 μm to 1 mm were prepared. It is remarkable that these free-standing $MAPbI_3$ wafers have a mirror-like reflective surface with a root-mean-square

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Spectroscopic study of NE8 defect in synthetic diamond for optical thermometry

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ABSTRACT

We carried out a laser spectroscopic investigation of high-pressure, high-temperature (HTHP) synthetic diamond containing NE8 defects. In the photoluminescence (PL) emission spectra the defects have a zero-phonon line (ZPL) at 794 nm. Under 730 nm excitation the width and position of the ZPL as well as the Debye-Waller factor showed systematic temperature dependences which were modelled in accordance of a modified model of impurity defects in solids. A strong dependence of the position of the 794 nm ZPL on temperature suggests that NE8-containing diamond could be suitable for sensitive optical thermometry above 200 K. Further, the PL in the NIR spectral range makes the diamond crystalline particles promising temperature sensors for biomedical applications.

1. Introduction

Doping of diamond has proved to be a fruitful way to create a number of photostable optical centres in an inorganic matrix. Moreover, the optical centres frequently show a pronounced sharp zero-phonon line (ZPL) in the absorption or emission spectra even at room temperature due to a high Debye temperature of diamond. The simultaneous occurrence of high photostability and room-temperature ZPLs is a unique property of the optical centres in diamond. Sharp spectral lines allow a high selectivity in both the excitation and emission of PL. Best known optical impurity centre in diamond is the nitrogen-vacancy (NV) centre with a ZPL at 637 nm, see a thorough review [1]. One can easily control the formation and concentration of the NV defects by an electron irradiation and subsequent annealing of nitrogen containing diamonds. There are several applications utilizing the NV defect, such as single photon emitters [2], optical markers for biomedical applications [3], optical thermosensor based on the measurement of Debye-Waller factor [4] and a nanosize magnetometer based on the triplet ground and excited states of the NV-defect [5]. A lot of attention has also been paid to the Si-vacancy (SiV) defect with a ZPL at 737 nm [6]. Nanodiamonds containing SiV defects were found to be suitable as optical biomarkers [7]. SiV defect has also allowed realizing the single photon emitter [8]. It was demonstrated that SiV defect retains its emitting capabilities even in very small ~2 nm molecular-sized nanocrystallites [9] in contrast to NV, which is emitting only if the size of nanocrystallites exceeds 30 nm [10].

In high-pressure, high-temperature (HPHT) synthetic diamonds several Ni-containing optical defects were found if Fe-Ni-C melt was used in the synthesis. Based on ESR and optical measurements it was concluded that the defect with a ZPL at 794 nm (so called NE8) can be assigned to Ni atom surrounded with four nitrogen atoms [11]. High-temperature post-annealing (up to 2200 K) is favourable to create NE8 optical defects [12]. A CVD method for preparation of diamond films containing NE8 defects has been devised [13]. The allowed 794 nm electronic transition of NE8 defect occurred promising as single photon emitters for telecommunication applications [14,15,16].

The principal goal of the current investigation was careful spectroscopic study of the NE8 optical defect in a Ni-doped HPHT diamond to assess the feasibility of the material as optical thermosensor operating close to room temperature in the NIR spectral range, as needed for biomedical applications.

2. Experimental

The diamond crystal was prepared by temperature gradient method using a polyanvil HPHT apparatus. The growth temperature was 1700 K at the pressure of 5.5 GPa and Fe-Ni-C served as solvent-catalyst [12]. The crystals were subjected to irradiation of 3.0 MeV electrons up the

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Determination of the complex refractive index of powder phosphors

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Abstract: We demonstrate a novel 2-step method to precisely determine both *n* and *k* of phosphors, luminescent inorganic particles, in the visible spectrum. To measure *n* we modified the Becke Line immersion method and verified its applicability in the absorption/ emission regions of phosphor particles (step 1). Particles were then embedded into a transparent binder and coated in thick layers (100-500 µm) on glass. Absorptance of the layers was measured with a novel approach: spectral angular resolved measurements. This method delivers accurate results by avoiding any errors from intense scattering inside the layers. A computational model was employed to extract *k* of particles from the measured absorptance data taking into account luminescence, scattering and re-absorption (step 2). The entire method was verified on reference materials. Finally, based on the proposed method, we determined in a broad wavelength range the *n* and *k* parameters for a variety of commonly used phosphors with few or no earlier reports on their *n* and *k* values (the complete set of numerical data is fully disclosed in the supplementary materials).

OCIS codes: (160.5690) Rare-earth-doped materials; (120.4530) Optical constants; (290.5850) Scattering, particles; (290.1483) BSDF, BRDF, and BTDF; (160.2540) Fluorescent and luminescent materials.

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Key parameters of efficient phosphor-filled luminescent down-shifting layers for photovoltaics

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Abstract

Spectral management is one of the promising ways to increase the efficiency of modern photovoltaic devices. We study the performance of phosphor-filled luminescent down-shifting (LDS) layers. We focus on four powder phosphors with refractive indices in the range of 1.66–1.84 and similar particle size distributions. Using experimental characterization as well as 3D optical simulations, we identify key parameters of the phosphor particles and LDS layers that primarily affect the optical transmittance, absorptance, and photoluminescence quantum yield of the layers. We investigate the influence of the medium located beneath the LDS layer and reveal a strong increase in the performance when the layer is applied directly onto the solar cell. Finally, the optimal combination of the particle, binder and layer parameters that render the highest performance of the LDS layers are also indicated and discussed.

Keywords: phosphors, photoluminescence quantum yield, transmittance, absorptance, photovoltaics

(Some figures may appear in colour only in the online journal)

1. Introduction

Improving the performance of solar cells is of crucial importance for competitiveness of photovoltaics (PV) among all the other sources of energy. Luminescent down-shifting (LDS) is an approach to increase the conversion efficiency of solar cells in the UV and near-UV spectral region (Richards 2006a, Klampaftis *et al* 2009). This is done by using a variety of photoluminescent materials (Alonso-Alvarez *et al* 2012, Meinardi *et al* 2014, Solodovnyk *et al* 2014). They are placed as a layer on top of solar cells in the solar PV module either embedded into transparent non-conducting binder materials, (van Sark *et al* 2010, Klampaftis *et al* 2011, Danos *et al* 2012, Klampaftis *et al* 2012, Ross *et al* 2012a, Erickson *et al* 2014, Uekert *et al* 2016) or in pristine form (Hong and Kawano 2003). These LDS layers absorb UV light and re-emit it in the visible regime where most solar cells have a much higher external quantum efficiency (EQE). As the major benefit, LDS layers are expected to improve conversion efficiency without any changes in the structure of the solar cell. For instance, Ross *et al* (2012b) experimentally showed that up to 9% increase in efficiency of the commercial CdTe (cadmium telluride) solar modules could be gained by means of application of a polymer layer doped with luminescent organic molecules.

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Light harvesting enhancement upon incorporating alloy structured $CdSe_xTe_{1-x}$ quantum dots in DPP:PC_{61}BM bulk heterojunction solar cells†

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Hybrid solar cells based on the pDPP5T-2 electron donating polymer, [6,6]-phenyl-C_{61}-butyric acid methyl ester (PC_{61}BM) and cadmium selenide telluride ($CdSe_xTe_{1-x}$) quantum dots (QDs) are fabricated and their photovoltaic performance and optoelectronic properties are investigated as a function of QD loading. The power conversion efficiency (PCE) of hybrid solar cells is improved up to 5.11% for the device containing 4 wt% of QDs which is mainly due to the enhancement in short circuit current density (J_{sc}) resulting from increased light harvesting. A full-fledged study is performed on the microstructure, charge transfer/transport and recombination mechanisms of our ternary hybrid solar cells by employing various advanced techniques. The transmission electron microscopy (TEM) results reveal the non-agglomerated and uniform distribution of the $CdSe_xTe_{1-x}$ QDs within the pDPP5T-2:PC_{61}BM host matrix at low QD concentrations. Transient absorption spectroscopy (TAS) showed a slower charge carrier recombination rate due to the introduction of QDs into the photoactive layer. It can be attributed to the more efficient exciton dissociation in ternary systems. These findings are consistent with the photovoltaic properties of the device.

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Introduction

Organic ternary photovoltaic devices are promising competitors with silicon based solar cells, since they have the potential to be manufactured by low-cost processes in a large scale and they can offer flexibility and transparency.[1] Most of these solar cells consist of a bulk heterojunction (BHJ) between light absorbing electron-donating (p-type) and electron-accepting (n-type) materials. Nevertheless, organic solar cells present several dilemmas and challenges: they suffer from low mobility, low exciton diffusion lengths and incomplete harvesting of the solar spectrum.[2] The last problem has been tackled by incorporating a second absorber like low band gap polymers,[3–11] small molecules[12–14] and dyes[12,15–17] as alternatives to more complicated multi-layer or multi-cell stacks.[18,19] Owing to the broader light harvesting, these ternary devices showed enhanced PCE.

Semiconductor QDs are also very promising sensitizers because of their special properties like easily tunable valence and conduction bands and band gap, versatile surface chemistry and compositional flexibility, potential multiexciton generation, small exciton binding energy, broad light harvesting and large absorption coefficients, to name a few.[20,21] Importantly, by tuning their size – due to the quantum confinement effect – they can be accurately modeled to fit the complementary absorption spectrum of the polymers. Furthermore, depending on their size, QDs can reflect and scatter light and therefore increase the optical path without the need of thicker layers that would be deleterious for the charge transport. QDs such as CdSe,[22–24] CdTe,[25] PbS[26–28] and InP[29] have been incorporated into polymeric host systems to improve the final PCE of the solar cell by broadening its absorption and optimizing charge dissociation, separation and collection.[30]

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Morphology-Controlled Organic Solar Cells Improved by a Nanohybrid System of Single Wall Carbon Nanotubes Sensitized by PbS Core/Perovskite Epitaxial Ligand Shell Quantum Dots

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In the present work, a new solution processed nanohybrid system comprising of single-wall carbon nanotubes (SWCNTs) loaded by PbS quantum dots (QD) capped with an epitaxial ligand shell of methylammonium lead iodide perovskite clusters (MA_4PbI_6) is designed and fabricated. Attachment of PbS/PbI_6 QDs on the surface of SWCNT is followed and evidenced by performing Fourier Transform Infrared Spectroscopy, X-ray photoelectron spectroscopy, and Field Emission Scanning Electron Microscopy. The steady state and dynamic photoluminescence results reveal efficient charge transfer from photo-excited PbS/PbI_6 to SWCNTs. Very low amount (0.3 wt.%) of the as-synthesized PbS/PbI_6-SWCNT is further incorporated into a polymeric solar cell containing P3HT and $PC_{61}BM$ and exhibits a power conversion efficiency improvement of around 15% compared to the P3HT:$PC_{61}BM$ bulk heterojunction reference solar cell. Significantly, loading perovskite capped PbS QDs on the surface of SWCNT works more efficient rather than incorporating PbS/PbI_6 or SWCNT separately onto the composition of the photoactive layer. While PbS/PbI_6 broaden the absorption window of photoactive layer and enhance the photon harvesting, their loading on the SWCNT has a significant influence on the faster exciton splitting by efficient electron transfer as well as keeping the desired crystallinity and nanoscale morphology of host matrix upon addition of QDs.

1. Introduction

Organic photovoltaic devices (OPV) have attracted great attention in the past few years as an alternative to expensive silicon-based solar cells due to the low cost of materials, inexpensive large area device production, as well as their flexibility and transparency.[1–3] Most of the organic solar cells are based on bulk heterojunction (BHJ) morphology which is normally comprised of p-doped (electron donor) and n-doped (electron acceptor) semiconducting materials.[4–7] Nevertheless inefficient exciton dissociation, low carrier mobility, and incomplete harvesting of the solar spectrum remain as bottlenecks for the ultimate device performance of organic solar cells.[8,9] The idea of incorporating a second photo absorber such as low band gap polymers,[10–18] small molecules,[19–21] and dyes[19–24] has been used to tackle the latter problem.

Colloidal semiconductor nanocrystals or quantum dots (QDs) have shown promising applicability in solution-processed transistors, solar cells, and other optoelectronic devices due to their high absorption coefficient, tunable band gap, multiple exciton generation with single photon absorption, tunable energy levels, slow exciton relaxation, and low cost.[25–29] In this sense, lead chalcogenide QDs such as PbS[30,31] and PbSe[32,33] are of particular interest due to their specific advantages, such as the narrow band gap (e.g., 0.41 and 0.28 eV for bulk PbS and PbSe, respectively) and large excitonic

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Review Article
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Recent Developments in Quantum Dots/CNT Co-Sensitized Organic Solar Cells

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Abstract

Polymer solar cells (PSCs) are emerging alternative candidates to the standard silicone technology for green and renewable energy generation owing to their flexibility and solution processability. Bulk heterojunction (BHJ) organic solar cells (OSCs) based on conjugated semiconducting polymers as donor (D) and fullerene derivatives as acceptor (A) offer large D/A interfacial area, which overcomes the short exciton diffusion length. Although, recent advances in narrow band gap semiconducting polymers have led to the improvement in power conversion efficiency of organic photovoltaics (OPVs) beyond 10%, inefficient charge separation and low carrier mobility as well as negligible photon harvesting in near-infrared (NIR) and/or infrared (IR) region of the solar spectrum have still remained as bottle neck for ultimate performance of OPVs. Most PSCs only absorb the UV-visible part of the solar spectrum, leading to the low light harvesting efficiency. Hence, solution processed photoactive materials comprising nanostructured semiconducting inorganic quantum dots (QDs) as sensitizer have attracted great attention to improve energy conversion efficiency of the OPVs. This is attributed to the outstanding optoelectronic properties of QDs such as band gap tunability, potential NIR photons harvesting and multi exciton generation (MEG). However, the main shortcoming of inorganic QDs based OSCs is randomly hopping charge transport among discrete QD particles, which can be tackled through hybridization with one dimensional (1D) electrically conductive nanostructured materials such as carbon nanotube (CNT). By this way, CNT particles would behave as support for anchoring the light harvesting semiconductor QDs, leading to the enhancement of the exciton dissociation and charge transport towards the corresponding electrodes. Recently, manufacturing PSCs co-sensitized by QD loaded CNT has been shown as a promising direction to maximize performance of the device. This article reviews the recent developments in enhancement of OPVs" performance by utilization of high efficient light harvesting QDs and/or their hybrid with 1D CNTs.

Keywords: Organic solar cell; Quantum dot; Carbon nanotube; Ternary solar cell; Hybrid solar cell

Introduction

In the past few years, there has been great growth in interest towards organic photoactive (OPV) technology as an alternative to expensive silicon based PV technologies, owing to its low cost of materials, inexpensive large area device production through e.g. ink jet or roll-to-roll printing techniques, environmental friendliness, high flexibility, and freedom of form [1,2]. Compared to the conventional silicone based solar cells, polymeric PVs give a wider selection of the photoactive materials to engineer the cell photon harvesting and boost the energy conversion efficiency [3-5]. In organic solar cells, the photoactive layer normally comprises p-doped (electron donor) and n-doped semiconducting materials (electron acceptor) that are blended to desired morphology [6-8]. To maximize charge generation, a large area interface between these two phases is required, which can be achieved by controlling and optimizing the photoactive micromorphology. The developed final microstructure of the coated photoactive layer is controlled by various parameters such as blend composition, rate of solvent evaporation, solution viscosity and rate of crystallization [8-11]. In spite of aforementioned merits of OPVs, they still suffer from lack of acceptable efficiencies [12]. Improvement of OSCs efficiency by various means such as synthesis of new materials, micro morphological optimization and applying advanced strategies such as multi-junction structures, ternary near-IR sensitization and hybrid organic-inorganic systems have been the scope of many researches during last decades [13-21]. The latter strategy will be the focus of this review.

Colloidal semiconductor nanocrystals or quantum dots have great potential for PV applications due to their high absorption coefficient, tunable band gap which is size dependent, multiple exciton generation with single photon absorption, tunable energy levels, slow exciton relaxation and low cost [13-16]. Despite such conceptual merits, QD based organic solar cells have demonstrated poor device performances as a result of randomly hopping charge transport among discrete QD particles. Besides, QDs phase separate from their organic matrix, thus developing a bicontinuous network is difficult.

Improvement in charge carrier separation and transport can be achieved via hybridization of QDs with one dimensional electrically conductive nanostructured materials such as CNT. In this way, CNT particles would behave as support for anchoring the light harvesting semiconductor QDs, leading to the enhancement of the exciton dissociation and charge transport towards the corresponding electrodes [22]. Unique optical and electronic properties of CNT as well as its wide electrochemical stability window, and high surface area render CNT as an excellent moiety in OSCs. As a consequence of such synergistic effect, BHJ polymer solar cells containing CNT/QD nanohybrid have attracted great attentions.

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Depth-resolved and temperature dependent analysis of phase formation processes in Cu–Zn–Sn–Se films on ZnO substrates

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Abstract The constitution of secondary phases in kesterite $Cu_2ZnSnSe_4$ (CZTSe) thin films is still a limiting factor for their application in solar cells. Therefore an enhanced understanding of phase formation processes during the fabrication of CZTSe films is required. In this study we present a temperature and film-depth dependent phase analysis of Zn/Sn/Cu precursors on ZnO substrates selenized at different temperatures. A special sample preparation step using a focused ion beam was applied to prepare shallow angle cross sections for depth-resolved Raman profiling of the thin films. At low selenization temperatures multiphase structures are demonstrated and a first formation of CZTSe besides secondary phases at only 250 °C is detected. At high selenization temperatures an accumulation of ZnSe at the interface of CZTSe and ZnO substrates is observed. Furthermore indications for the formation of a thin SnO_2 interface layer were found by X-ray diffraction, secondary electron microscopy and energy dispersive X-ray spectrometry.

1 Introduction

The kesterite material $Cu_2ZnSn(S,Se)_4$ (CZTSSe) has emerged as an interesting alternative semiconductor for thin film solar cell applications. This is motivated by its formation of earth abundant elements which allow low material costs and the low toxicity of the constituents compared to established thin film solar cell technologies. An absorption coefficient in the order of 10^4–10^5 cm^{-1} in the visible range [1, 2] and a band gap between 1.0 eV for the pure selenide CZTSe and 1.5 eV for the pure sulfide CZTS [3] has been reported.

Best power conversion efficiencies of >12% have been demonstrated by a two-step fabrication process with solution-based precursor deposition and subsequent thermal treatment in a chalcogen atmosphere [4]. Highest performances for devices are shown in literature for Cu-poor and Zn-rich compositions [5], i.e. $Cu/(Sn+Zn)\approx 0.9$ and $Zn/Sn\approx 1.2$ which is clearly off-stoichimetric. However, at this composition the formation of the binary ZnSe or ZnS phases which are known to have a limiting effect on solar cell performance [6] can be expected. Additionally, decomposition reactions of CZTSSe during the high temperature annealing step in fabrication processes are known to cause secondary phases [7, 8] and can occur at the front surface as well as the CZTSSe/Mo back contact interface. The decomposition at the surface, which is connected to tin loss can be prevented by introducing SnSe or SnS into the annealing atmosphere [9]. The decomposition at the back contact which is connected to the formation of $MoSe_2$ or MoS_2 can be hindered by modified back contacts with intermediate TiN or ZnO layers [10, 11].

Despite these strategies to suppress the decomposition reactions in CZTSSe films, the understanding of phase formation mechanisms during annealing is important for controlling secondary phase formation and thus improving material quality and solar cell efficiencies. Studies on the phase formation of CZTSSe mainly using in-situ or ex-situ X-ray diffraction (XRD) and surface sensitive Raman spectroscopy have already been reported [12–14]. However

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Cellular interfaces with hydrogen-bonded organic semiconductor hierarchical nanocrystals

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Successful formation of electronic interfaces between living cells and semiconductors hinges on being able to obtain an extremely close and high surface-area contact, which preserves both cell viability and semiconductor performance. To accomplish this, we introduce organic semiconductor assemblies consisting of a hierarchical arrangement of nanocrystals. These are synthesised via a colloidal chemical route that transforms the nontoxic commercial pigment quinacridone into various biomimetic three-dimensional arrangements of nanocrystals. Through a tuning of parameters such as precursor concentration, ligands and additives, we obtain complex size and shape control at room temperature. We elaborate hedgehog-shaped crystals comprising nanoscale needles or daggers that form intimate interfaces with the cell membrane, minimising the cleft with single cells without apparent detriment to viability. Excitation of such interfaces with light leads to effective cellular photostimulation. We find reversible light-induced conductance changes in ion-selective or temperature-gated channels.

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Quasi-epitaxial Metal-Halide Perovskite Ligand Shells on PbS Nanocrystals

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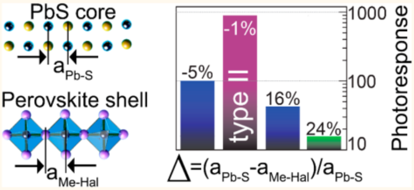
Supporting Information

ABSTRACT: Epitaxial growth techniques enable nearly defect free heterostructures with coherent interfaces, which are of utmost importance for high performance electronic devices. While high-vacuum technology-based growth techniques are state-of-the art, here we pursue a purely solution processed approach to obtain nanocrystals with eptaxially coherent and quasi-lattice matched inorganic ligand shells. Octahedral metal-halide clusters, respectively 0-dimensional perovskites, were employed as ligands to match the coordination geometry of the PbS cubic rock-salt lattice. Different clusters $(CH_3NH_3^+)_{(6-x)}[M^{(x+)}Hal_6]^{(6-x)-}$ (M^{x+} = Pb(II), Bi(III), Mn(II), In(III), Hal = Cl, I) were attached to the nanocrystal surfaces *via* a scalable phase transfer procedure. The ligand attachment and coherence of the formed PbS/ligand core/shell interface was confirmed by combining the results from transmission electron microscopy, small-angle X-ray scattering, nuclear magnetic resonance spectroscopy and powder X-ray diffraction. The lattice mismatch between ligand shell and nanocrystal core plays a key role in performance. In photoconducting devices the best performance (detectivity of 2×10^{11} cm Hz $^{1/2}$/W with > 110 kHz bandwidth) was obtained with $(CH_3NH_3)_3BiI_6$ ligands, providing the smallest relative lattice mismatch of *ca.* −1%. PbS nanocrystals with such ligands exhibited in millimeter sized bulk samples in the form of pressed pellets a relatively high carrier mobility for nanocrystal solids of ~1.3 cm^2/(V s), a carrier lifetime of ~70 μs, and a low residual carrier concentration of 2.6×10^{13} cm^{-3}. Thus, by selection of ligands with appropriate geometry and bond lengths optimized quasi-epitaxial ligand shells were formed on nanocrystals, which are beneficial for applications in optoelectronics.



KEYWORDS: *nanocrystals, perovskite, conductive ligands, epitaxy, photodetectors, optoelectronics, semiconductors*

Epitaxy, the deposition of crystalline layers of ordered atoms from gaseous or liquid precursors on top of crystalline substrates, is of major importance in research and industrial semiconductor technology to produce conditioned materials, quantum-structures, and devices with "tailor-made" characteristics.[1−3] Epitaxial materials based on (ultra) high-vacuum technologies benefit from the excellent control over deposition rates, low defect densities, atomically sharp interfaces, precise composition control, and the possibility to fabricate structures of variable dimensionality.[1,2] Solution-based epitaxial growth has also been achieved, for instance, to obtain oriented nanowires on planar substrates[4,5] or to overcoat dispersed micro- and nanostructure quasi-substrates with thin functional films[6] of oriented nanoparticles.[7] Epitaxial solution growth is widely used today in colloidal chemistry to obtain core/shell structures with various morphologies[8−20] to reduce surface recombination of photoexcited carriers,[8,10,13] to tune the attractive interactions between quantum confined electrons and holes,[21,22] to manipulate nonradiative Auger recombination,[23−25] or to improve the materials environmental stability.[10]

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Effect of post-annealing treatment on the structure and luminescence properties of AlN:Tb^{3+} thin films prepared by radio frequency magnetron sputtering

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Keywords: Rare earths, terbium, aluminum nitride, cathodoluminescence, wide bandgap semiconductor, photoluminescence exitation

Abstract. Terbium-doped aluminum nitride thin films have been deposited by radio frequency magnetron sputtering. The influence of annealing treatments on structural, morphological and luminescence properties of the films is examined with the aim to optimize post-deposition annealing conditions. Temperatures starting from 500 up to 1000°C using two annealing techniques were investigated: rapid thermal processing and quartz tube furnace. X-ray diffraction analysis revealed the formation of aluminum oxide and aluminum oxynitride phases at temperatures higher than 750°C. The oxygen content in the surface layer was measured with energy dispersive X-ray. The terbium emission was obtained after excitation either by photons or electrons. The films treated with rapid thermal processing at 750°C resulted in the highest emission.

Introduction

Aluminum nitride (AlN) is a wide band gap semiconductor that has attracted interest as a host for rare earth (RE) elements, due to its favorable thermal, electrical and optical properties [1]. The large band gap of AlN (~6.2 eV) not only allows transparency for RE emission, but also is convenient to overcome the quenching of RE emission at room temperature [2, 3]. The almost host independent emission color is a special feature of the RE ions. They are an alternative to the common band-to-band transition emission, where the gap of the host determines the color of the device [4]. An advantageous way to produce semiconductor thin films doped with RE ions is by magnetron sputtering deposition, due to its high-throughput production and high quality films [5]. Post-deposition annealing treatments are used to improve the emission intensity of the RE ions and the film structure causing crystallization and grain coarsening [6, 7]. More important, however, in the development of luminescent materials is that annealing can influence the activation mechanisms of the RE emissions [6, 8, 9].

This work investigates two annealing techniques to increase the emission intensities of Tb doped AlN films: rapid thermal processing (RTP) and quartz tube furnace (QTF). The films were annealed at various temperatures between 500°C and 1000°C. At each annealing step, cathodoluminescence (CL) spectra of the Tb emissions are measured. The effect of annealing temperature on the structure and composition of the produced films is evaluated using X-ray diffraction (XRD) and energy dispersive X-ray (EDX). The findings from the structural and luminescent characterization of AlN:Tb^{3+} and the optimal annealing temperature is reported.

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REVIEW

Power Electronic Semiconductor Materials for Automotive and Energy Saving Applications – SiC, GaN, Ga_2O_3, and Diamond

Peter J. Wellmann*[a]

Dedicated to Professor Wolfgang Schnick on the Occasion of his 60th Birthday

Abstract. Power electronics belongs to the future key technologies in order to increase system efficiency as well as performance in automotive and energy saving applications. Silicon is the major material for electronic switches since decades. Advanced fabrication processes and sophisticated electronic device designs have optimized the silicon electronic device performance almost to their theoretical limit. Therefore, to increase the system performance, new materials that exhibit physical and chemical properties beyond silicon need to be explored. A number of wide bandgap semiconductors like silicon carbide, gallium nitride, gallium oxide, and diamond exhibit outstanding characteristics that may pave the way to new performance levels. The review will introduce these materials by (i) highlighting their properties, (ii) introducing the challenges in materials growth, and (iii) outlining limits that need innovation steps in materials processing to outperform current technologies.

1 Introduction

Automotive and energy saving applications include a number of electronic switching systems capable to distribute electrical power between energy supply, storage, and consumption devices. The performance level may range from (i) low power (10 W to 1 kW) and low voltage (< 400 V) applications like power supplies for consumer electronics and low performance mechatronic systems, via (ii) mid power (1 kW to 100 kW) and mid voltage (400 V to 1.2 kV) applications like electric motor controls, photovoltaic inverters, electric vehicle drives, and universal power supplies to (iii) high power (MW to GW) and high voltage (mainly 1.7 kV to 6.5 kV, but certain devices at higher voltages) applications like rail transport, ships, wind mills, and smart power grid. Basically in all cases the control and transformation of electrical currents (AC → AC, AC → DC, DC → AC, and DC → DC) stand in the foreground.

For high power devices and systems, reliability is the most important issue. Therefore novel materials with extraordinary properties may be used. Opposite, in the low power case, manufacturing costs dominate by far and established mass production processing technologies using standard materials stand in the foreground. In the mid power range, reliability and costs have to be balanced. New technologies are needed but they need to be based on large area, high throughput processing routes.

In power electronics semiconductor diodes and transistors that are able to operate at high voltages, currents, and power densities as well as increasingly higher switching frequencies of several hundred kilohertz are necessary. From a materials perspective the prerequisites may be broken down to three physical properties: (i) a high break down field E_B enables electronic devices to withstand high voltages during operation and provides a great robustness against unintentional operation failure, (ii) a large heat-conductivity λ improves the dissipation of heat loss and lowers the device operation temperature, and (iii) a great charge carrier saturation velocity vs. supports high frequency operation for more efficient electric power con-

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Investigation of deep electronic levels in n-type and p-type 3C-SiC using photoluminescence

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Abstract

Among the various SiC polytypes, cubic 3C-SiC is much more difficult to grow in high crystalline quality than the commercially introduced hexagonal 6H-SiC and 4H-SiC counterparts. Besides some benefits of 3C-SiC for transistor applications related to a greater electron mobility and a lower metal-oxide-semiconductor interface trap density compared to 4H-SiC, new potential optoelectronic applications have been introduced very recently. Boron doped 3C-SiC may act as an ideal candidate for an intermediate band (IB) solar cell material. Aluminum doped p-type 3C-SiC could lead to the development of efficient optoelectrochemical water splitting cells. Finally, 3C-SiC with its various intrinsic point defects has been considered as a suitable candidate for future spintronic-applications. All these applications will critically depend on further understanding defect behaviour on atomic level. In our study we investigated free standing n-type and p-type 3C-SiC material grown in our lab. Temperature dependent photoluminescence measurements revealed the presence of carbon vacancy related V_C and V_C-C_{Si} defect transitions in the p-type materials but not in the n-type materials. This observation present in as grown 3C-SiC is believed to have significant impact on the optoelectronic applications. Copyright © 2017 VBRI Press.

Keywords: 3C-SiC, doping, p-type, defects, carbon vacancy.

Introduction

In recent years, SiC has gained much interest as a semiconductor material for energy saving applications. Its unique physical properties like great break down field, great electron saturation velocity and great heat conductivity make it superior over silicon in the case of power electronic devices. For an overview on the growth of SiC boules see e.g. [**1-6**]. Other applications of SiC make use of its superior radiation hardness (X-ray and g-ray detectors), chemically inertness (biomedical coatings) and very low nuclear magnetic moment (spintronic) [**7-11**].

The cubic 3C-SiC is known to be much more difficult to grow in high crystalline quality than the hexagonal 6H-SiC and 4H-SiC counterparts. The 3C-SiC is more attractive in certain transistor applications related to a greater electron mobility and a lower metal-oxide-semiconductor interface trap density compared to 4H-SiC. More importantly for energy applications, the p-type doping by B and Al presents interest in new optoelectronic applications, the combination of suitable bandgap and high electron mobility in 3C-SiC together with the almost perfect deep level position of B make 3C-SiC an ideal candidate for an intermediate band (IB) solar cell material [**12-13**]. Aluminum doped p-type 3C-SiC reduces the oxidation of 3C-SiC and could allow development of efficient opto-electrochemical solar driven water splitting cells for hydrogen generation [**13-15**]. Prospectively, 3C-SiC with its various intrinsic point defects is very promising for future spintronic quantum computing applications [**7,11**]. All these activities are supported by a continuous progress in the growth of quasi bulk cubic SiC (see e.g. [**17-21**]).

In this study we have prepared freestanding n-type and p-type 3C-SiC material. Temperature dependent photoluminescence measurements is well known as an established tool to explore SiC properties, and suitable to distinguish intrinsic point defects in the n and p-type material. It is particularly useful in case of potential spintronic applications, and it is noteworthy that the studied point defect occurs in as grown p-type 3C-SiC rather than being formed using implantation techniques [**7,11**].

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Growth, Defects and Doping of 3C-SiC on Hexagonal Polytypes

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Technologies for the growth of 3C-SiC with crystalline quality and crystal size similar to hexagonal counterparts (6H- or 4H-SiC) are still at the laboratory stage. There are several challenges in the control of polytype stability and formation of structural defects which have to be eliminated to reveal the full potential of this material. Nevertheless, 3C-SiC has been explored for various energy, environment and biomedical applications which significantly benefit from the intrinsic semiconductor properties of this material. The future of 3C-SiC and its applications depends on the advances which will be made in improving crystalline quality, enlarging crystal size and controlling doping levels which have not been entirely explored due to the lack of high quality 3C-SiC substrates. This paper reviews recent progress in growth and doping of thick 3C-SiC layers on hexagonal SiC substrates using sublimation epitaxy. It covers the growth process on off-axis substrates and defects occurrence, as well as the issue of obtaining high resistivity material.

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In recent years cubic silicon carbide (3C-SiC) has been regaining its importance among other SiC polytypes in development of various semiconductor device applications. In addition to active devices it can be used as a substrate for growth of high quality nitrides or epitaxial graphene layers.[1,2] The quality of the latter greatly benefits from the absence of the energy driven step bunching which occurs in the hexagonal polytypes upon heating above a certain temperature due to the anisotropy of the crystal structure. The high electron mobility (~1000 $cm^2V^{-1}s^{-1}$) and lower bandgap (~2.3 eV) of 3C-SiC, compared to hexagonal SiC polytypes, enabled researchers to demonstrate the best channel mobility values among the SiC-based MOSFETs devices.[3] There are also innovative applications like intermediate band solar cells, photo electrochemical devices for water splitting, quantum communication or biomedical applications which significantly benefit from the intrinsic 3C-SiC properties.[4–9]

Due to the lack of bulk 3C-SiC crystals, hetero-epitaxial growth on Si or hexagonal SiC substrates is used to obtain 3C-SiC material with a size suitable for device fabrication. However, such 3C-SiC does not demonstrate the full potential of its intrinsic semiconductor properties due to a high density of defects, e.g. stacking faults, which are formed at the 3C-SiC/substrate interface. This problem is more pronounced in 3C-SiC grown on Si due to the large mismatch in lattice parameters and thermal expansion coefficients, despite that growth of a large area 3C-SiC and the majority of functioning devices, varying from MOSFETs to MEMS, have been demonstrated using such material.[10–18] Therefore, it can be expected that mastering the growth and doping of 3C-SiC on hexagonal SiC substrates, especially providing high resistivity 3C-SiC material, would allow validating semiconductor devices of improved performance.

In this paper, we present an overview on the growth and doping of thick 3C-SiC layers grown on hexagonal SiC substrates using sublimation epitaxy performed at Linköping University. Such layers can be used as substrates for homoepitaxial structures and as seeds for the bulk growth of 3C-SiC material.

Sublimation Epitaxy

Originally, sublimation epitaxy was developed for the growth of thick homoepitaxial 4H- or 6H-SiC layers.[19] Later, it was demonstrated in several studies that it can be adopted for the growth of 3C-SiC material.[20–23] The growth setup consists of an inductively heated graphite crucible inserted in graphite insulation. Inside the crucible the materials are stacked in a sandwich-like arrangement as shown in Fig. 1. Tantalum (Ta) foil is placed at the bottom, the source material, in a form of a CVD or PVT grown polycrystalline SiC plate, on top of it followed by the graphite spacer, the substrate and the graphite plate. The driving force for the growth is the temperature difference between the source, which is placed in a higher temperature zone, and the substrate. The distance between the source and the substrate is usually adjusted between 1 to 4 mm. The vapor phase stoichiometry above the SiC source or substrate is thermodynamically fixed and depends on temperature. Since Ta acts as a carbon getter at elevated temperatures, it reacts with carbon bearing species and forms TaC.[24] In this way, the vapor phase composition can be enriched with Si species which is believed to be beneficial for 3C-SiC polytype stability.[25,26] Moreover, the growth of 3C-SiC is performed at temperatures below 2000°C which also provides a more silicon enriched growth environment due to the higher partial pressure of silicon compared to other species sublimating from SiC.[27] In addition, the growth ambient is typically vacuum (E^{-5} mbar) which allows, in the frame of the growth geometry, kinetically limited mass transport of the vapor species leading to high 3C-SiC growth rates reaching 1 mm/hour in our growth system.

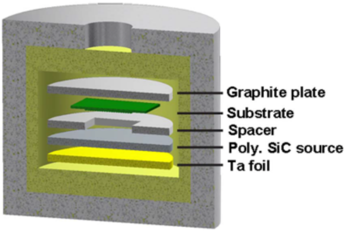

Figure 1. Sublimation epitaxial growth arrangement in cross section.

On-Axis vs Off-Axis Hexagonal SiC Substrates

Most of the growth studies of 3C-SiC on SiC by sublimation techniques were made using nominally on-axis hexagonal SiC substrates.[22,28–31] Nominally on-axis surfaces contain large terraces on which the probability to exceed the supersaturation threshold needed

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Overcoming the Thermal Instability of Efficient Polymer Solar Cells by Employing Novel Fullerene-Based Acceptors

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Extensive research efforts around the world have been devoted to organic photovoltaics (OPV) over the last decade due to their unique advantages for commercial application, such as low cost, light weight, flexibility, and easy manufacture on large-scale.[1–3] By introducing the bulk heterojunction (BHJ)[4,5] structure into OPV devices, tremendous progress has been achieved to boost the power conversion efficiency (PCE) of OPV devices to the 11% regime.[6–9] The most efficient polymer donors, such as poly(benzodithiophene-co-thieno[3,4-b]thiophene) (PBDTTT)-based polymers,[7] diketopyrrolopyrrole-based polymers,[10] and poly[(5,6-difluoro-2,1,3-benzothiadiazol-4,7-diyl)-alt-(3,3‴-di(2-nonyltridecyl)-2,2′;5′,2″;5″,2‴-quaterthiophen-5,5‴-diyl)] (PffBT4T-C_9C_{13}),[6] possess bandgaps of 1.40–1.60 eV and achieve the highest performance so far in combination with the commonly used methanofullerene derivatives like phenyl-C_{61}-butyric acid methyl ester ([60]PCBM) or [6,6]-phenyl-C_{71}-butyric acid methyl ester ([70]PCBM).[11]

Functional fullerenes, on the one hand, can preserve the properties of pristine fullerenes, such as superior electron-transporting ability and high electron affinity. On the other hand, by properly attaching suitable addends, one can manipulate a wide variety of chemical, physical, or thermodynamic properties, such as better solubility in organic solvents, higher lowest unoccupied molecular orbital (LUMO) level, and improved compatibility with organic donors.[12] These advantages endow functional fullerenes with extraordinary capability, acting as unique electron-accepting components in OPV devices.[2,13] Although PCBM is the most prominent acceptor in OPV devices,[5,14] the energy levels of PCBM should be further optimized in order to achieve high open circuit voltage (V_{OC}) in combination with the state-of-the-art organic donors.[15] Fullerene derivatives with more suitable electronic levels are expected to reduce the bandgap to V_{OC} loss and approach the theoretical efficiency limit.[13,16] PCBM bisadduct[17] and indene-C_{60} bisadduct[18] made their glory debut for being well compatible with poly(3-hexylthiophene-2,5-diyl) (P3HT) and for achieving promising high V_{OC} and PCE compared to the PCBM-based counterparts. However, resulting from constitutional isomer impurities and inefficient charge generation, fullerene bisadducts failed to produce similarly satisfying performance with the latest outstanding organic donors.[19] Another effective way of increasing the LUMO level of fullerene derivatives is to add an electron-donating group to the fullerene cage.[20] A series of newly developed functional fullerenes have shown higher photovoltaic performance than PCBM resulting from their high-lying LUMO levels. Itoh and co-workers carried out a systematic study on a series of fulleropyrrolidine derivatives, some of which possess higher V_{OC} and efficiency than PCBM when blended with P3HT.[21] Troshin and co-workers reported that solar cells based on the novel pyrrolidinofullerene acceptors exhibited impressively high V_{OC} and promising efficiency in combination with Poly[*N*-9′-heptadecanyl-2,7-carbazole-*alt*-5,5-(4′,7′-di-2-thienyl-2′,1′,3′-benzothiadiazole)] (PCDTBT) and P3HT compared to the PCBM-based references.[22]

As the PCE of OPV devices was improved to over 11%, currently, more research efforts are required to address the long-term stability issue. Many factors may cause degradation

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Understanding the correlation and balance between the miscibility and optoelectronic properties of polymer–fullerene solar cells†

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Organic photovoltaics is one of the most promising technologies for sustainable green energy supply. Because of their high electron affinity and superior electron-transporting ability, fullerene-based materials are deemed as very strong electron-accepting components in organic solar cells. However, the most widely used fullerene-based acceptors, such as phenyl-C_{61}-butyric acid methyl ester, exhibit limited microstructural stability and unsatisfactory thermal stability owing to their insufficient compatibility with organic donors. Here, we in-depth investigate the carrier dynamics along with structural evolution and analyze the acceptor loadings in optimized bulk-heterojunction (BHJ) solar cells as a function of the polymer–fullerene miscibility. The polymer–fullerene miscibility has more influential effects than the crystallinity of single components on the optimized acceptor : donor ratio in polymer–fullerene solar cells. The findings demonstrated in this work suggest that the balance between the miscibility of BHJ composites and their optoelectronic properties has to be carefully considered for future development and optimization of OPV solar cells based on BHJ composites. Miscibility is proposed in addition to crystallinity as a further design criterion for long lived and efficient solar cells.

Introduction

Owing to the advantages of light weight, easy fabrication, low cost and flexible devices, worldwide research efforts have been devoted to thin-film organic photovoltaics (OPV) in the past two decades.[1–12] The active layers of organic solar cells are commonly composed of blends of an electron donor and an electron acceptor. After introducing the bulk-heterojunction (BHJ)[1,2] concept for the active layers, enormous progress has been made in every aspect of OPV technology.[13–27] [6,6]-Phenyl-C_{61}-butyric acid methyl ester ($PC_{61}BM$) and its corresponding C_{70} analogue $PC_{71}BM$ have been the most prominent acceptor materials over the last two decades, and achieved the efficiency milestones in combination with various benchmark polymer donors, such as poly[2-methoxy-5-(3′,7′-dimethyloctyloxy)-1,4-phenylenevinylene] (MDMO-PPV),[3,13] poly(3-hexylthiophene-2,5-diyl) (P3HT),[4] poly[2,6-(4,4-bis-(2-ethylhexyl)-4*H*-cyclopenta[2,1-*b*;3,4-*b*′]dithiophene)-*alt*-4,7(2,1,3-benzothiadiazole)] (PCPDTBT),[8] poly((3-fluoro-2-[(2-ethylhexyl)carbonyl]thieno[3,4-*b*]thiophenediyl)) (PTB7),[28] poly[4,8-bis(5-(2-ethylhexyl)thiophen-2-yl)benzo[1,2-*b*;4,5-*b*′]dithiophene-2,6-diyl-*alt*-(4-(2-ethylhexyl)-3-fluorothieno[3,4-*b*]thiophene-2-carboxylate-2-6-diyl)] (PTB7-Th)[11,29] and poly[(5,6-difluoro-2,1,3-benzothiadiazol-4,7-diyl)-*alt*-(3,3‴-di(2-octyldodecyl)-2,2′;5′,2″;5″,2‴-quaterthiophen-5,5‴-diyl)] (PffBT4T-2OD).[30] The unique properties of functional fullerene acceptors are mainly related to pristine fullerenes, such as great electron-transporting ability and high electron affinity. The adducted organic group of fullerene-based acceptors can be chemically modified to tune their solubility in organic solvents and compatibility with organic donor materials, which makes the functional fullerene acceptors so successful in the field of OPV technology.[20,24,31–33]

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Noble-Metal-Free Photocatalytic Hydrogen Evolution Activity: The Impact of Ball Milling Anatase Nanopowders with TiH_2

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In 1972, Fujishima and Honda[1] reported photoelectrochemical water splitting into hydrogen and oxygen using a titania semiconductor single crystal as photoanode. This finding triggered immense research activities on the direct conversion of photoenergy to chemical energy (hydrogen) using suitable semiconductors.[2–5] Except for photoelectrochemical approaches to produce H_2 (titania as a photoelectrode), the most direct photocatalytic way is to use semiconductor nanoparticles in suspensions of H_2O – with or without sacrificial agents. In general, the two greatest challenges in using TiO_2 for photoelectrochemistry and photocatalysis are, on one hand, the large bandgap (allowing only for UV activation of a photocatalytic reaction) and, on the other hand, the kinetically suppressed charge carrier transfer reactions for H_2 and O_2 generation.

To tackle the first challenge, numerous doping and bandgap engineering approaches have been explored over the past decades to shift the TiO_2 absorption into the visible light range of the solar spectrum by introducing suitable metal[6–8] or nonmetal[9] species into the TiO_2 lattice. Most recently, self-doping and particularly the generation of visible light absorbing "black TiO_2" have attracted wide interest. To this end, a large range of reduction conditions has been investigated, namely annealing in reducing atmospheres[10–12] (Ar, Ar/H_2, H_2), cathodic reaction, chemical reduction reactions, oxidation of Ti^{2+}/Ti^{3+} precursor,[13] ion-bombardment,[14,15] or implantation.[16] Most of these treatments of TiO_2 lead to classic Ti^{3+}/O_v defects, from which its black or dark-blue color and, thus, visible light absorption evolves. Such defects have also been reported to have some effect on the general photocatalytic activity of titania.[2,3,17]

The second challenge intrinsic to TiO_2, namely the sluggish H_2 generation kinetics in bias-free photocatalysis, is usually tackled by decorating TiO_2 nanoparticles with noble metal cocatalysts including Pt, Pd, Au, etc. These cocatalysts act as electron transfer mediators and enable "reasonable" H_2 evolution rates under open circuit conditions.[18–20] The use of low abundant noble metals questions, however, the economic benefit of using low-cost TiO_2-based catalysts for H_2 generation.

In a number of recent reports,[21–23] some specific modifications of TiO_2 are shown to substantially increase the photocatalytic activity for H_2 evolution without any noble-metal decoration. The formation of intrinsic defects, that is, specific configurations of Ti^{3+} or vacancies (O_v) are responsible for the unexpected activity, as they act as cocatalytic centers in TiO_2 that facilitate the electron transfer to the adjacent phase.

In other words, although there is a wide range of ways to introduce Ti^{3+} and O_v defects into titania, it is only in a few limited cases that these states act as efficient and stable cocatalytic centers for H_2 evolution under open circuit conditions. Successful treatments are high pressure hydrogenation or H-ion implantation.[21,22] As such, the benefits of creating an intrinsic cocatalytic activity seem to originate from synergetic interactions between defects and hydrogen that is present during these treatments.

In this work, we demonstrate that a well-established and facile ball milling approach using mixtures of commercial anatase nanoparticles and TiH_2 introduces noble-metal-free photocatalytic H_2 activity to titania. We characterize this synergistic effect in view of the nature of defects, state of hydroxylation, and investigate the effect on the energetics and kinetics of electronic states and the resulting H_2 evolution performance.

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Conference Proceedings

Claudia Buerhop, Thilo Winkler, Sven Wirsching, Tobias Pickel, Andreas Bemm, Christian Camus, Jens Hauch, Christoph J. Brabec
Analyzing the degradation of pre-damaged PV-modules
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Claudia Buerhop, Frank W. Fecher, Tobias Pickel, Tirth Patel, Cornelia Zetzmann, Christian Camus, Jens Hauch Christoph J. Brabec
Impact of PID on industrial rooftop PV-installations
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Analyzing the degradation of pre-damaged PV-modules

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ABSTRACT

Cracked PV-modules are frequently detected in PV-systems. The impact of cracked cells on the energy yield and module performance under real operating conditions is not yet understood but of great relevance. Standard tests cannot reveal the relevant information conclusively. Therefore, we conducted a twofold analysis. 1) field exposure (global analysis on string level as well as detailed analysis on module level), and 2) load testing in the lab. Here, we present comparative electro-luminescence (EL-) images recorded in an outdoor test stand and during load testing. Additionally, infrared (IR-) images as well as power data obtained from loaded and operating (field) conditions are discussed.

Keywords: pre-cracked modules, field tests, loading tests, power measurements, IR-imaging, performance loss

1. INTRODUCTION

The presence of damaged modules, especially with cell cracks and fractures, can be frequently observed in contemporary PV-installations which have been in service for some years[1, 2]. Up to now, most investigations, standards and test procedures focus on degradation of new, defect-free modules[3, 4]. To date, the degradation and lifetime of pre-stressed, pre-cracked modules with existing crack structures at real operating conditions is still not understood.

Origins for crack formation are manifold[5, 6]: manufacturing, soldering/metalization[7], handling, transportation[8], installation, vandalism, and site-specific operating conditions. These include in addition to extreme weather conditions, such as hailstorms, also maintenance work like cleaning. There are several special methods to detect cracks in solar cells[9-11]. Most frequently EL-imaging is used for visualizing cracks. Such cracks can influence the power performance[12-17] of the modules. Special mechanical loading tests allow the differentiation between open and closed cracks and their impact on the module performance[18-22].

This study highlights the degradation and its influence on module performance of pre-cracked PV-modules with existing cracks at real operating conditions and mechanical load testing in the lab. At real operating conditions planar loads like snow and wind as well as temperature cycles (daily and annual) stress installed (pre-cracked) PV-modules. Therefore, well-monitored field analyses as well as accelerated, but more realistic load tests are carried out[19]. A twofold approach is chosen to get a better understanding of degradation of pre-cracked modules: 1) Global and detailed analysis of outdoor-exposed modules are carried out. The global study includes continuous monitoring of electric (string level) and weather data and occasional EL-imaging and IV-measurements on module level. The detailed analysis provides additionally electric information on module-level of serially connected modules. 2). For accelerated stress testing a newly developed set-up for load testing is used. It allows the experimental simulation of planar load by under- or overpressure, which is typical for snow and wind loads. Simultaneous EL-imaging precisely records crack initiation and growth as well as crack opening under load and crack closure at unloaded stage.

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Impact of PID on industrial rooftop PV-installations

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ABSTRACT

Potential induced degradation (PID) causes severe damage and financial losses even in modern PV-installations. In Germany, approximately 19% of PV-installations suffer from PID and resulting power loss. This paper focuses on the impact of PID in real installations and how different evaluated time intervals influence the performance ratio (PR) and the determined degradation rate. The analysis focuses exemplarily on a 300 kWp PV-system in the Atlantic coastal climate. IR-imaging is used for identifying PID without operation interruption. Historic electric performance data are available from a monitoring system for several years on system level, string level as well as punctually measured module string I-V-curves. The data sets are combined for understanding the PID behavior of this PV plant. The number of PID affected cells within a string varies strongly between 1 to 22% with the string position on the building complex. With increasing number of PID-affected cells the performance ratio decreases down to 60% for daily and monthly periods. Local differences in PID evolution rates are identified. An average PR-reduction of -3.65% per year is found for the PV-plant. On the string level the degradation rate varied up to 8.8% per year depending on the string position and the time period. The analysis reveals that PID generation and evolution in roof-top installations on industrial buildings with locally varying operation conditions can be fairly complex. The results yield that local operating conditions, e.g. ambient weather conditions as well as surrounding conditions on an industrial building, seem to have a dominating impact on the PID evolution rate.

Keywords: potential induced degradation (PID), IR-imaging, performance ratio, performance loss

1. INTRODUCTION

Potential induced degradation (PID) of photovoltaic (PV) modules is a failure mode that has become more prevalent during the last years[1]. An interview with operators of many big PV-plants in 2016 revealed that about 19% of the PV-plants may suffer from PID or PID-suspicion[2]. Since PID causes severe damage and power loss in PV-modules[3, 4], an enormous financial loss can be the consequence for operators and investors.

This failure module, PID, is explained by sodium ion diffusion from the glass into the solar cell[5]. The diffusion process is forced by high potential gradients, temperature and humidity[6, 7]. PID observations have grown because the system voltage or string voltage of PV-systems increased[8]. PID appears in crystalline solar cells[9, 10] as well as in thin film technologies[11, 12]. Several stress tests for simulating PID have been developed[13, 14] and show the voltage reduction, power loss and degradation of PID-affected cells in electroluminescence images (EL).

In PV-installations, infrared (IR)[15, 16] and EL-imaging[17] are used to detect and visualize PID without operation interruption. The use of drones accelerates the inspection[11, 18] and provides a good overview of the degradation of the modules[19]. Thermographic images have the potential, that the power loss of the module due to PID can be determined quantitatively[16, 20].

This case study focuses on the analysis of the actual quality of a PID-affected PV-system as well as on study of its temporal change. Since imaging inspections are normally carried out occasionally, it is important to know the characteristics and detectability of PID using available monitoring data, like power output, yield, which are collected

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Lifetime and Degradation of Pre-damaged PV-Modules – Field study and lab testing

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***Abstract* — The presence of pre-cracked PV-modules in modern PV-plants is well-known. The evolution and actual impact of the cracks on electrical yield under real operation conditions is not yet understood but of great relevance. Established standards cannot reveal the relevant effects. Therefore, a unique threefold analysis is applied: 1) field exposure, 2) using a new accelerated loading test, and 3) Finite Elements (FEM) simulations. For the first time, we present comparative Electroluminescence (EL-) images recorded in the field and during load testing. Crack growth is studied in terms of the monitored weather conditions and the applied load simulating static snow and wind loads.**

I. INTRODUCTION

Here, "*pre-cracked*" describes the existence of cracks in at least one single cell of the investigated PV-modules before the beginning of the analyses. The interest in lifetime and prospective performance of pre-cracked PV-modules [1, 2] gains in importance. Nowadays, electroluminescence (EL)imaging routines exist allowing the on-site inspection of PV-plants for installed and partially defective PV-modules [3]. Therefore, the degradation of such modules, e. g. with cracks, is of great interest for operators, investors and insurances. Today's standards [4] and most scientific work focuses on degradation of new, defect-free PV-modules. Some work is done on mechanical loading and fatigue tests [5, 6]. At operating conditions the mechanical loads due to wind and snow are known as the most critical stresses for crack growth in solar cells [7]. They can be calculated according to guidelines for loads to load-bearing structures [8, 9].

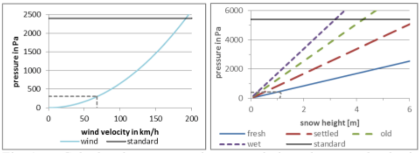

Fig. 1. Calculated pressure due to wind and snow loads in comparison with the pressure of the standard load tests [4]

Standards for testing pre-cracked modules do not exist. Known standards [4] differentiate the variety of existing load scenarios, as displayed in Fig. 1. Typical values from field experience for wind and snow are marked by grey lines, wind speed $v_{\text{wind}} = 65$ km/h and snow height $h_{\text{snow}} = 1.1$ m, respectively. Standard tests stress the modules much more, see dark solid lines. The pressure data are calculated for typical module installations with a tilt angle of 35°.

First experience of the degradation of pre-cracked modules at real operating conditions are documented by periodically repeated EL-imaging and power measurements [10].The aim of this paper is a deeper understanding of the field performance of pre-cracked modules by further experiments and Finite Elements (FEM) simulations. Additional strain measurements enable the recording of the local displacement and can verify the FEM-simulations of mechanical stress distribution in solar cells during loading.

II. EXPERIMENTAL PROCEDURE

Our threefold approach includes field exposure of PV-modules, performing artificial load tests with a newly designed test-setup in the lab, and finally, supplementary FEM simulations computing mechanical stress.

A. *PV-modules and field tests*

For this investigation, pre-cracked, crystalline PV-modules (230 W, 60 cells) from a landslide claim were investigated. They had differing numbers of cells with cracks and fracture. Most cracks were identified parallel and near the busbars (Fig. 4, Fig. 5).

During the field exposure several parameters were recorded, as described elsewhere [10]. Highly resolved weather (solar irradiance, ambient temperature, wind speed, humidity) and module data (module temperature, string current, string voltage) were collected by a monitoring system. In addition, punctually EL-imaging and IV-measurements of individual modules were carried out. Furthermore, the strain present within the modules was measured. Therefore, strain gauges (Tokyo Sokki Kenkyujo Co., Ltd.), especially adapted to glass, were attached to the cover glass in the center of the modules. Using strain rosettes (composite material strain gauge of series "F" FRA-2-8) the gauges are separated by 45°.

PERFORMANCE ANALYSIS OF PRE-CRACKED PV-MODULES AT REALISTIC LOADING CONDITIONS

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ABSTRACT: Damaged modules, especially with existing cell cracks, are observed quite often in PV-installations. Little knowledge exists about the stability of such pre-cracked modules under real operating conditions. Previous investigations and existing standards focus on the degradation of new, defect-free modules. This work highlights a twofold approach for performance study of pre-cracked modules: 1) artificial stressing of 20 representative pre-cracked modules with a novel load test set-up simulating snow and wind loads, 2) simulating IV-curves of cracked cells. The experimental results are discussed with respect to field exposure data. EL-images of stressed PV-modules indicate that new cracks are only initiated once a certain threshold is exceeded. Below this threshold formerly unseen cracks open, as can be seen by small changes in the EL-intensity. Power measurements yield a strong power reduction at the loaded state. Due to the solar cell being under tension the cracks open and the separated areas lose their electrical contact. Considering a break resistance in the IV-curve, simulations lead to good agreement with the observed experimental results.

It is highlighted that the electric contact after unloading for the previously unloaded module recovers visibly in the EL-image as well as in the power output. Simulating real weather (operating) conditions by moderate static loading tests reveals no measurable changes in the EL-images affecting the power output.

Keywords: EL-imaging, pre-cracked modules, cracks, degradation, performance.

1 INTRODUCTION

Quality control of PV-installations is of great interest today. Imaging methods, such as thermography (infrared) IR-imaging and electroluminescence (EL) imaging, are commonly used to visualize defective modules and their location [1-3].

Fig. 1 shows an aIR-image of a PV-plant. aIR-imaging means a drone-mounted IR-camera is used for the inspection [4]. The cells with homogeneously increased temperatures are typical for cell fracture [5]. Using EL, cracks as well as fractures can be detected/visualized in detail [6, 7]. Statistical analysis reveals that many PV-plants suffer from modules with cell fracture [1].

How cracks and fractures influence the lifetime and future performance under real operating conditions is still not known completely, yet. At operating conditions, the modules are exposed to various stresses, e. g. temperature cycles, wind and snow loads.

Existing standards and standardized test procedures do not provide the relevant information [8] for lifetime prediction of pre-cracked modules.

Therefore, the crack evolution in PV-modules for “realistic” weather conditions is studied. A one-year field study in Southern Bavaria [9] shows the mean daily wind speed is approx. 32 km/h, the most frequent wind speed is about 28 km/h and a maximum wind speed of about 140 km/h was observed only in a single storm.. The snow coverage can be rather low. Daily module temperature cycles range up to 60 K while the air temperature differs for the same period by maximum 20 K. Applying existing standards for structures [10, 11] corresponding wind loads, $p(v{=}30\text{ km/h}) \approx 150$ Pa and , $p(v{=}140\text{ km/h}) \approx 1300$ Pa are investigated. Respectively, for snow load results $p(\text{height of fresh snow} = 1\text{ m}) \approx 500$ Pa.

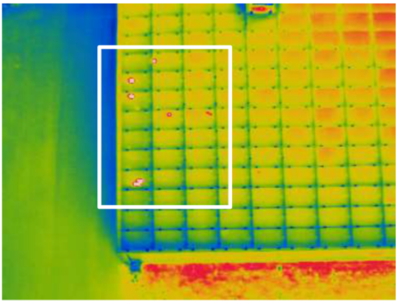

Fig. 1: aIR-image of PV-plant with several modules showing locally increased temperatures due to cell fracture

For a better understanding of the future lifetime of pre-cracked modules we decided on a twofold approach: combining field exposure with lab testing and additional electrical simulations - the latter two being highlighted in this paper by computer simulating realistic loading conditions and monitoring crack growth simultaneously. The load test facility as well as the first results will be presented in this paper.

2 EXPERIMENTAL PROCEDURE

For this investigation pre-cracked, crystalline PV-modules (230 W) from a landslide damage were investigated exhibiting differing numbers of cells with cracks and fracture. Many cracks were identified in parallel and in vicinity to the busbars.

QUANTITATIVE STUDY OF POTENTIAL INDUCED DEGRADATION OF A ROOF-TOP PV-INSTALLATION WITH IR-IMAGING

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ABSTRACT**:** Potential induced degradation (PID) causes severe damage and financial losses even in modern PV-installations. In Germany, approximately 19% of PV-installations suffer from PID and resulting power loss. This paper focuses on the impact of PID in real installations. The analysis focuses exemplarily on a 314 kWp PV-system in the Atlantic coastal climate. Infrared (IR)-imaging is used for identifying PID without operation interruption. Historic electric performance monitoring data for several years are analyzed on system and string level. Additionally, punctually measured module string current-voltage (I-V)-curves are considered. The data sets are combined for understanding the PID behavior of this PV plant. The number of PID affected cells within a string varies strongly between 1 to 22% with the string position on the building complex. A PID-resistance which correlates to the defined PID-defect-ration is presented. Finally, indicators for the reliable determination of PID is given.

Keywords: potential induced degradation (PID), IR-imaging, PID criteria, power loss, PID-resistance

1 INTRODUCTION

Potential induced degradation (PID) of photovoltaic (PV) modules has been a defect type becoming more and more relevant during the last years. PID causes severe damage and financial losses even in modern PV-installations. In Germany, approximately 19% of PV-installations suffer from PID [1]. This paper focuses on the understanding of PID generation in real installations.

Fig. 1: Aerial picture of the roof installation of the investigated PV-plant on an industrial building. Positions of outlets emitting heat or dust are marked by the numbers 1 to 6. A, B, C, and D define different types of roof areas. The color code indicates the defect ratio of the strings [2]. (Imagery © 2017 Google, Map data © 2017 Google)

In this paper, we investigate a 314 kWp PV-plant on an industrial roof-top installation in Portugal exhibiting severe PID damage. Evaluation of the monitoring data of this PV-plant was challenging due to partial shading by various roof installations (chimneys and other roof outlets) resulting in inhomogeneously irradiated modules within the module string. Additionally, the diefferent roof areas exhibited varying orientation and strings were connected in a complex manner. (cf. fig 1). The annual energy yield for the last three years of operation was rather constant and gave no indication for accelerated degradation of the PV-plant [3]. Nonetheless, the monitoring data revealed degradation upon detailed analysis.

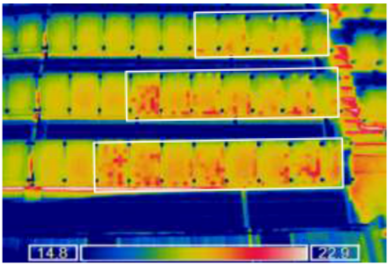

Fig. 2: aIR-image of the roof-top installation showing many PID-affected modules marked with frames

Aerial infrared (aIR) inspection has the property that it may be used for the direct visualization and localization of the PID-degraded modules [4-7], see fig. 2.

Besides monitoring data of the maximum power point (MPP) at string level and IR-imaging, electro-luminescence (EL) imaging, current-voltage (*I-V*) measurements (on module and module string level) and weather data completed our investigations. By these data, the performance ratios of the PV-plant and the module strings were evaluated and the distribution of PID-affected modules within a string as well as the locations of PID-cells within modules were analyzed.

Previous results [2, 3, 6] published on this PV plant are extended here by introducing a new parameter for characterizing PID.

2 EXPERIMENTAL PROCEDURE

A 314 kWp PV-plant installed in 2013 and located in the Atlantic coastal climate was examined. It consists of 1280 poly-crystalline PV-modules of P_{nom} = 245 Wp, 60 strings, and 15 inverters. Each string electrically connects 15 to 24 modules. The nominal open circuit and maximum power point (mpp) voltage are V_{oc} = 37.1 V and V_{mpp} = 30.3 V. For a string with 20 modules the voltages are 890.4 V and 727.2 V, respectively. We use the following

STATISTICAL ANALYSIS OF INFRARED-INSPECTIONS OF PV-PLANTS

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ABSTRACT: First statistical evaluation of IR-inspections of PV-plants reveals that 81% of the installed PV-plants show IR-abnormalities. More than 140 PV-plants with more than 200,000 PV-modules were inspected and evaluated statistically. Main IR-abnormalities or failures in modules and string installations are analyzed, respectively. The average failure rate for PV-modules is about 6% and for module strings approximately 1%. The differentiation based on the installation type reveals that small residential installations relatively seen show more defective modules than large field installations. A first estimation of the missed income by not detecting and maintaining major module and plant failures yield a missed income of about 100 Mio. EUR considering the PV-systems installed in Germany. IR-imaging is a valuable method to give fast and reliable information about the actual quality and failure rate in inspected PV-installations.

Keywords: IR-imaging, statistics, failure, performance.

1 INTRODUCTION

Quality control of PV-plants is of increasing interest for service and maintenance. Failures in PV-installations may cause a safety risk as well as a severe power reduction and poor performance in the future. Therefore, many studies have been carried out about the reliability of PV-modules in the past years. Also, there are various surveys of failure rates of PV-modules during operation [1-8].

Among the top ten module failure mechanisms are: connector failures and glass breakage as retrieved from field inspections [6]. The data presented suggest that 34% of the inspected modules have some type of failure. The IEA report [1] states that the most important failures in the field are junction box failure, glass breakage, defective cell interconnect, loose frame and delamination. De Graaff's [3] survey points out that 2% of the modules do not meet the manufacturer warranty. After a certain life time the most dominant module failures are delamination, cell fracture and discolouration [7]. Most investigations focus on the impact on the actual power output.

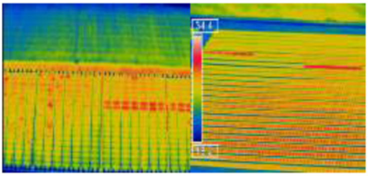

Fig. 1: aIR-images of two PV-plants showing different defect sites, left: industrial roof installation with numerous defective modules and two suspicious module strings, right: IR-overview of a field installation with two suspicious module strings

In order to check the PV-plant quality and locate and identify potential failures IR-inspections are a valuable tool. Drone-based measurement systems enhance the fast, mobile, flexible and non-destructive inspection under real operating conditions without operation interruption [9]. Electrically malfunctioning modules show up in the IR-image because of their elevated temperature [10]. This drone-based IR-inspection is called aIR-imaging and respectively aIR-images or IR-images. Typical IR-images of two different installations are presented in Fig. 1. Here, module and string failures can be distinguished. A module failure normally shows single sites (small spots, individual cells, cell arrays typically protected by a bypass diode, so called substring) of increased temperature within the module. A String failure is typically caused by a cabling problem of installed PV-modules, e. g. the connection to the inverter is interrupted. The modules within the string are at open circuit. No current flow is possible and so finally all absorbed solar irradiation is transferred to heat. Therefore all these modules show a homogeneously higher temperature.

The scope of this paper is to present an updated overview of the abnormalities in IR-inspections of PV-plants based on a statistical evaluation of the data collected in the last years. Thereby the evaluation is governed by the question "*what are typical occurrences for IR-findings and how are they distributed and influenced?*" A yield discussion concludes the paper.

2 EXPERIMENTAL PROCEDURE

The aIR-inspections were carried out with a measurement system consisting of a drone equipped with an IR- and VIS-camera and various sensors. The drone is an unmanned aerial vehicle (UAV). Here an octocopter is used which is equipped with a navigation system and various sensors.

During the last years a large number of PV-generators were investigated. They differ in cell technology (crystalline and thin film), in power output (kWp), in the number of modules, operation duration and installation location (industrial roof, residential roof, field installation, tracker) and geographic location. IR-inspections of approximately 140 PV-plants are evaluated statistically in this paper. Their peak power adds up to roughly 52 MWp with about 400,000 installed PV-modules. Mostly, PV-plants with crystalline silicon cell technology were analyzed. That means, 95% of the inspected PV-plants and roughly 40% of the investigated PV-modules are of crystalline technology.

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SPECIAL ISSUE PAPER

WILEY PROGRESS IN PHOTOVOLTAICS

Verifying defective PV-modules by IR-imaging and controlling with module optimizers

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Abstract

Quality control and efficient operation of roof-top residential photovoltaic (PV)-installations is an economic and technical challenge because these PV-systems often suffer from various roof orientations and inclinations as well as partial and temporal shading. Module optimizers, which track the operating point individually for each module group, are good solutions providing also additional electrical information. The purpose of this work is verifying the identification and localization of defective PV-modules with infrared (IR)–imaging and with module optimizers as well as quantifying the impact on the performance. Several PV-plants were inspected and carefully analyzed. The findings using IR-imaging can clearly be classified to substring failures due to open circuit and short circuit, bypass-diode faults, cell defect, and some undefined optimizer problems. The electric data reveal that these findings are related to certain power loss and monthly or annual yield reduction. Interesting is the temporal behavior of particular defective sites, which show short-term recovery. In summary, there is a good agreement between the occasionally performed IR-findings and the continuously monitored electrical data.

KEYWORDS

defects, IR-imaging, module optimizer, monitoring, thermography, yield

1 | INTRODUCTION

Infrared (IR)–imaging is widely used for quality inspection of photovoltaic (PV)–plants.[1-3] Defective modules are reliably detected at operating conditions. The benefit of this method would be increased even more if the impact on the module performance could be quantified. Data originating from the solar simulator are of limited usefulness since operating conditions cannot be mimicked. Operating conditions means that the modules are at elevated temperatures, have a varying temperature distribution, are connected in series, and therefore interact and influence each other. Defective modules within a string configuration impact current and voltage of the overall string maximum power point (MPP) and accordingly the defect temperature.[4] In contrast, module optimizers control 1 or 2 modules; thus, a limited interaction of the modules is possible.

As a first approach, a test facility was built up to study the correlation between IR-measured defect temperatures and module performance.[4] This motivated a study on the assessment for IR-inspection and efforts on system design and improvement of real PV-installations.[5]

In a cooperative study, the experiences are now used to verify both IR-inspection and module-level monitoring in terms of defective module detection and quantification of their impact on the performance.

Module level control systems, so-called module optimizers, are frequently installed in residential roof-top PV-plants. Here, the modules are exposed to varying solar irradiance, so that string inverters are not the best solution. Shading, differing roof orientations and inclinations are some of the reasons. To avoid performance losses of the PV-system due to partial shading under series-connection conditions, module optimizers can limit the losses.[6]

This paper, for the first time, sheds light on IR-inspections of real PV-systems with a quantitative defect assessment based on module optimizers. Of interest is the impact of the MPP-tracking (MPPT) of the module optimizers on the defect temperature difference and the resulting yield loss. Because of reduced mismatch, these numbers should be lower than for standard string solutions. Thus, for the same defect, lower impact is expected. For the first time, IR-inspection results are compared to power and yield data from module-level–optimized

A NEW METRIC FOR ASSESSING LOCAL MECHANICAL LOAD SCENARIOS FOR PV MODULES AT SPECIFIC LOCATIONS

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ABSTRACT: In this paper, a new metric for assessing the location-specific mechanical loads imposed by snow or wind gusts which a photovoltaic module can be expected to be exposed to at a given location is introduced. For demonstrating this general approach, two locations of moderate distance (~110km) in Northern Bavaria are compared. It is shown that even on moderate distances the expected loads differ by a factor of four or more highlighting the importance of location-specific requirements for PV modules. For assessing the loads, the historical weather data of the closest surrounding weather station is evaluated in order to deduce an expectation value for the site of interest. This data is analyzed with respect to the frequency and severity of the relevant weather events such that the annuality of a weather event of a given severity can be determined. Finally, the severity of an event corresponding to a single occurrence in 20 years, i.e. a standard product warranty, is chosen to represent the requirements of a location with respect to a certain parameter.

Keywords: Photovoltaic, Forecast, Reliability, Weather

1 INTRODUCTION

Nowadays, photovoltaic (PV) modules are usually manufactured according to certain IEC standards, which are meant to assure product safety and reliability. However, these standards usually test a certain set of conditions or scenarios, independently from the actual location at which a particular module is going to be installed in the end. Thus, a module will always overfulfil many local requirements whilst possibly failing one in which its properties might not be sufficient for a particular location finally leading to a module failure within its expected lifetime or even guarantee period.

Especially, in times of high price pressure on the manufacturer side it would be highly desirable to cut down requirements where they are too strict, whilst ensuring robustness where needed. As most PV modules are going to be installed at their installation time for their entire technical lifetime a customization to the local requirements in terms of climate parameters or safety demands would be possible and highly desirable. However, in order to do so a method is needed to assess the climatic conditions for any given location for deducing the respective requirements.

Among the climate conditions affecting module reliability one has to distinguish between factors which lead to a constant ageing of the module and the materials therein, such as UV dose temperature cycles and factors for which the most severe single event can be expected to be most relevant. Mechanical loads can be assumed to belong to the latter group with wind gusts and snow loads being the most critical ones for non-desert climates.

According to present data for differentiating the wind conditions for e.g. Germany only a very coarse site classification can be made. For instance, DIN EN 1991 1 4, which provides a wind zone map for Germany, categorizes entire Bavaria, Hesse, Baden-Wuerttemberg as well as parts of Rhineland-Palatinate and North Rhine-Westphalia as one single category. For the so-called Test Reference Years (TRY) published in [1], 15 weather regions are differentiated for Germany, which still constitute a rather coarse classification scheme, even though they can be modulated by factors accounting for elevation and urbanity. Furthermore, the TRYs only state hourly values, thereby automatically neglecting wind gusts which can be expected to constitute a major factor in mechanical load-induced PV module degradation.

Here, an approach for a site-specific assessment for expected loads is presented exemplarily for mechanical loads imposed by wind gusts and snow loads which can generally be transferred to any other parameters such as UV irradiation, temperature cycles etc., even though slight modifications might be needed. Thus, here meteorological snow and wind gust data will be used to deduce a long-term forecast for the site-specific stress exposure due to mechanical loads, whereas to date snow forecasts have been mainly discussed in terms of yield forecasting as snow covering prevents the modules from power generation [2,3].

2 GENERAL APPROACH

Currently, various studies focus on the determination of regional degradation rates by monitoring modules installed at various locations all over the world [4]. However, though yielding highly important data, these studies are limited by two facts: Firstly, they analyze the integral influence of the local weather, so the influence of a single parameter on the degradation cannot be deduced. Secondly, by nature these studies are very time-consuming as the modules degrade in real-time. Thus, it will take several years to be able to determine the regional lifetime differences for modules. This paper's approach aims at overcoming these limitations by using a standardized statistical analysis approach for assessing expected mechanical loads due to snow and wind. Thus, a 20-years-projection can be obtained right away and single parameters can be separated. This method then allows for deducing location or region-specific qualification-tests for any given location, which are tailored for assessing the suitability of a module for the respective location and

Algorithmus zur IR-Panoramabilderstellung aus IR-Luftaufnahmen von PV-Freiflächenanlagen

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1 Einleitung und Motivation

In Deutschland gab es Ende 2015 ca. 1,5 Millionen installierte PV-Systeme mit einer Gesamtnennleistung von ca. 40 GW, welche bereits einen relevanten Beitrag zur Stromversorgung liefern [1]. Besonders im Hinblick auf ältere PV-Bestandsanlagen mit unbekanntem Degradationsgrad gewinnen Vorhersagen über die kurz-, mittel- und langfristige Anlagenperformance an Bedeutung. Für die notwendigen, kontinuierlichen Instandhaltungsmaßnahmen der installierten PV-Module werden zuverlässige und effiziente Qualitätsbeurteilungsmethoden benötigt, welche unter anderem die schnelle Detektion von sicherheitsrelevanten Mängeln gewährleisten sollten.

In diesem Zusammenhang kann beispielsweise die Infrarotthermografie (IR) für die Qualitätsbewertung von PV-Modulen genutzt werden. Das kontaktlose, zerstörungsfreie Verfahren ermöglicht eine Qualitätsbeurteilung in Echtzeit und unter realen Betriebsumgebungen. Temperaturauffälligkeiten in IR-Aufnahmen von PV-Modulen weisen dabei auf Unregelmäßigkeiten hin, welche oft durch existierende Defekte in PV-Modulen verursacht werden [2, 3, 4, 5]. Dazu gehören beispielsweise heiße Punkte („Hot Spots“) und erwärmte Flächen.

Um Thermografieaufnahmen von PV-Freiflächenanlagen aus der Luft zu erhalten, mit welchen thermisch auffällige PV-Module eindeutig lokalisiert werden können, werden seit einigen Jahren vermehrt ferngesteuerte Fluggeräte einsetzt [6, 7]. Durch die Identifizierung und Klassifizierung defekter PV-Module wird der Ist-Zustand einer PV-Freiflächenanlage festgestellt, welcher in Verbindung mit aufgezeichneten Wechselrichterdaten eine genaue Abschätzung des tatsächlich zu erwartenden wirtschaftlichen Ertrages einer PV-Freiflächenanlage bis zu ihrem geplanten Laufzeitende ermöglicht [8].

Qualitative und quantitative Auswertung regelmäßig durchgeführter aIR-Inspektionen von PV-Anlagen mit typischem PID-Muster

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Einleitung

Potential induzierte Degradation (PID) von Photovoltaik (PV)-Anlagen wird immer öfter an PV-Anlagen diagnostiziert und kann den Ertrag innerhalb weniger Jahre nach der Installation drastisch reduzieren. Als Ursachen werden lange Modulstrings mit hoher Systemspannung von ca. 800 V oder mehr sowie Temperatur und Feuchte im Wechselspiel mit der Verkapselung genannt [1]. Neuste Untersuchungen gehen davon aus, dass grob geschätzt 19 % der PV-Anlagen in Deutschland PID-Probleme haben [2]. Da PID zu einer zeitlich fortscheitenden Verschlechterung der Anlagen führt, ist es wichtig, möglichst frühzeitig PID und dessen Schadensgrad festzustellen, um erfolgreich Gegenmaßnahmen zu ergreifen. Zur Verifikation von PID wird vielfach Elektrolumineszenz (EL) aber auch Infrarot (IR)-Thermographie herangezogen [3, 4]. Da IR-Inspektionen schnell, zuverlässig und kosteneffizient Hinweise auf PID in Solaranlagen ohne Betriebsunterbrechung geben, ist es unser Ziel, eine Methode zur schnellen Diagnose von PID vorzustellen, die gleichzeitig eine quantitative Bestimmung des Schädigungsgrads und regelmäßige Nachmessungen erlaubt.

In diesem Artikel stellen wir typische PID-Muster anhand von Infrarotluftaufnahmen (aIR) vor. Die Auswertung dieser zeigte auch erste Zusammenhänge zum Leistungsverlust der PV-Anlage. Des Weiteren wurde das Fortschreiten der PID in den

Best Student Paper

Inkjet-printed polymer-based scattering layers for enhanced light outcoupling from top-emitting organic light-emitting diodes

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ABSTRACT

High refractive index polymer-based scattering layers used as internal light extraction layers are a promising low-cost approach to enhance the luminous efficacy of organic light-emitting diodes (OLEDs). In order to avoid damaging of the OLED layers a structured and contactless deposition method for the polymer-based scattering layers is required. For enhanced lifetime of the devices the water diffusion through the scattering layer has to be eliminated by a structured patterning technique. Inkjet printing offers both a contactless and structured deposition. In this study we evaluate inkjet printing of nanocomposite polymer-based scattering layers for OLEDs. A detailed view on the material and process development is given. This involves an optimization of ink formulation, printing parameters as well as layer formation. The resulting haze values of the scattering layers at 550 nm vary between 40% and 90% for different layer thicknesses. The gain in external quantum efficacy of top-emitting OLEDs induced by light scattering compared to reference devices peaks at a factor of 2.3. The obtained results are discussed and verified by an optical volume scattering simulation model which will be presented in full detail. Also a parameter variation study and its impact on extraction efficiency will be shown.

Keywords: OLED, inkjet printing, internal light extraction, scattering layer

1. INTRODUCTION

In recent years organic light-emitting diodes (OLEDs) have attracted large scientific and industrial interest due to their potential applications in display technology and solid-state lighting [1-3] and have found its way into the commercial market in the last years [4]. However, in spite of the OLED commercialization a large drawback is the still high price per lumen compared to other lighting devices (for instance the LED) which has to be reduced in order to be competitive in the future [4].

One major effect limiting the luminous efficacy of OLEDs are optical losses introduced by refractive index variations in the device setup. For a device consisting of an organic layer stack (where the light is generated) with a refractive index of $\eta \sim 1.8$, sandwiched between a reflective metallic cathode on the one side and a semi-transparent ITO/glass-substrate (both $\eta \sim 1.5$) on the other side, only approximately 20% of the generated light leaves the device [5-8]. 30% and 50% of the generated light, which is isotropically emitted in all directions, is trapped by total internal reflection at the glass/air interface and within the organic/ITO multilayer region, respectively. Numerous approaches have been taken to enhance light outcoupling by introducing additional device structures [6], which can be separated into external (applied on the outside glass/air interface) and internal (built-in the layer structure, for example between the glass and the ITO layer) light extraction techniques. Since external enhancement methods only access the glass modes leading to only 30% light

SEPARATING THE INFLUENCE OF MATERIAL COMPOSITION AND LOCAL DEFECTS ON THE V_{OC} OF CIGS SOLAR MODULES

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ABSTRACT: In spite of the steadily improved quality of co-evaporated Cu(In,Ga)Se_2 absorber layers, the existence of local defects affecting the module performance in large area production can still be an issue. Generally, both, lateral composition gradients and point defects can be found in those layers. We show the necessity to separate these two influences and propose two measurement techniques in order to asses the effect of the material and the defects individually. In oder to quantify the theoretical defect-free open circuit voltage (V_{oc}), given by the material composition, we used luminescence spectroscopy. The additional effect on the V_{oc} originating from local defects was determined using dark lock-in thermography. The combination of both these methods enables a local prediction of a module's V_{oc}. In the following, we conduct an indepth analysis of the determination of the material composition and its impact on the resulting V_{oc}.

Keywords: CIGS, Defects, Electroluminescence, Monitoring, Spectroscopy

1 INTRODUCTION

Like any photovoltaic (PV) technology, Cu(In,Ga)Se_2 (CIGS) devices strive for even higher efficiencies [1]. Currently, full-size modules are not yet able to reach the record performance values small cells exhibit. In order to transfer these efficiencies to the module level, process development needs to be guided by a quality control tool, which examines performance losses as well as their causes. These losses can be traced back to at least two independent issues. On the one hand the material composition determines the electrical properties of the solar modules. On the other hand, defects like shunts impair the power output of the devices. It is essential to realize that these two factors contribute individually to the module performance. Neither the assessment of merely the material composition, nor the analysis of the defects alone is sufficient for a performance prediction.

In the following, we show the relation between open circuit voltage (V_{oc}) and the luminescence peak wavelength emitted by CIGS photovoltaic samples. Therefore, we compare single cells, for which it is possible to isolate certain properties and defect conditions, with mini modules. In order to provide a scientific relevance of the data we analyzed more than 40 samples for each size.

2 TECHNICAL DETAILS

In order to understand the particular impact of the material composition and the defects individually, we started by analyzing 30 mm x 4 mm PV cells. The advantage is that composition deviations are rather neglectable on such a small area (at least when aiming for assessing performance of a whole module). Furthermore, this approach yields samples of varying defect densities, allowing for separating its impact on cell performance from compositional effects. Subsequently, we moved on to the investigation of mini modules with 16 cell stripes on an 85 mm x 85 mm area. All cell and mini module samples were cut out of a full-size (1200 mm^2 x 600 mm^2) co-evaporated CIGS PV module. All modules were processed in the same way. The structure from bottom to top is glass substrate, a Mo back electrode, a CGIS absorber, a CdS buffer layer, an i-ZnO highly resistive layer, a ZnO:Al front electrode, covered by an encapsulation foile and glass [2].

In order to assure that we only observe the influence of the material composition, we excluded single cells with point defects, using dark lock-in thermography (DLIT) [3][4][5]. The chosen samples exhibited varying ratios of Ga and In. These compositions were determined using X-ray fluorescence spectroscopy (XRF) and are usually expressed as the elemental ratio [Ga]/([Ga]+[In]), called GGI. The used XRF device (custom-built model, Amtec, Germany) requires approximately 30 s for each data point and can only be applied at the non-encapsulated sample.

The electroluminescence (EL) setup used for the investigation of the material influence is a fiber coupled spectrometer (AvaSpecNIR256-1.7, Avantes, Netherlands), sensitive in the NIR range (InGaAs detector: 880 nm – 1620 nm). An additional collimator collects radiation within a measurement spot of ca. 1 mm diameter. The samples are excited using an electrical power source. 1 V was applied per cell (hence, 16 V for mini modules). Additional photoluminescence (PL) measurements were done, using a 532 nm laser as excitation source with a illumination intensity of about 7000 W/m^2. One data point is acquired in less than a second. The evaluation of the spectra is done using an analysis tool programed in Matlab. It fits a polynomial of 4th order around the maxima of the spectra, in order to get a continuous curve and determines its peak wavelength. This helps to increase the accuracy (of determining the peak) even beyond the resolution of the spectrometer which is limited to 3 nm.

Highly luminescent $Ca_3Sc_2Si_3O_{12}$:Ce^{3+} silicate garnet nano- and microparticles with 50-70% photoluminescence quantum yields as efficient phosphor converters for white LEDs

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ABSTRACT

We present a novel synthesis method of $Ca_3Sc_2Si_3O_{12}$:Ce^{3+} nano- and microparticles with outstandingly bright photoluminescence. Nanoparticles were synthesized by the co-precipitation method, where a long-chain fatty acid salt was used as the precipitation agent for Ca, Sc and Ce water solutions in combination with SiO_2 nanoparticles or TEOS as a silica source. Further calcination in reducing atmosphere results in brightly luminescent $Ca_3Sc_2Si_3O_{12}$:Ce^{3+} nanopowders with up to 50% photoluminescence quantum yield (PLQY). The modified conventional solid-state reaction was utilized for synthesizing microparticles. Pre-synthesis of metal and silicon oxide solid blends with subsequent high-temperature post-treatment enables to obtain $Ca_3Sc_2Si_3O_{12}$:Ce^{3+} microparticles with the record-high PLQY of about 70%. Additionally, both kinds of samples display significantly higher thermal stability of photoluminescence in comparison to a commercial YAG:Ce phosphor.

Keywords: $Ca_3Sc_2Si_3O_{12}$:Ce^{3+}, white LED, phosphor converter, nanopowder, co-precipitation

1 INTRODUCTION

Solid state lighting divices based on a combination of violet/blue light emitting diodes (LEDs) and phosphor convertors has created enormous commercial interest because of its potentially higher efficacies and long lifetimes. Step by step, the white light emitting diodes (WLEDs) replace the traditional light sources, due to their environmental friendless: the efficiency of the WLEDs is higher than that of fluorescent tubes and the WLEDs do not content mercury and other harmful elements. At present, a blue LED chip and a yellow emitting $Y_3Al_5O_{12}$:Ce^{3+} (YAG:Ce) phosphor is a conventinal WLED device [1]. However, research is going on to optimize parameters like the color rendering index or the color correlated temperature of WLEDs. One alternative phosphor is $Ca_3Sc_2Si_3O_{12}$:Ce^{3+} (CSS:Ce) silicate garnet phosphor. In the general, the silicate garnet phosphors are of interest, because they show high quantum yield with a broadband emission spectra and, furthermore, a high thermal stability.

Shimomura et al. reported in 2007 [2] the synthesis and optical properties of $Ca_3Sc_2Si_3O_{12}$ silicate garnet doped with cerium for an application in white LEDs. The synthesis was done by general solid-state reaction to produce the phosphor. A broadband photoluminescence emission with a maximum at around 505nm in the green spectral region and an excitation peak at 455 nm in the blue spectral region was demonstarted and the CIE color coordinates were calculated to be x=0.30 and y=0.59. The XRD patterns showed the pure phase of CSS silicate garnet. The phosphor also showed a high thermal stability. This is very important because it is well known that due to heat generation in LEDs in normal use the luminescence can drop due to quenching effects. Compared to $(Y,Gd,Ce)_3Al_5O_{12}$:Ce CSS:Ce shows remarkably high thermal stability up to 200°C. For example, at a temperature of 150°C it still shows a relative intensity of over 90% compared to around 55% in YAG with Gd.

Further researches has been done by Chen et al. in 2010 to estimate the effect of different fluxes on the luminescence properties of the green CSS:Ce phosphor [3]. The phosphors were produced via solid state synthesis by firing in a reducing atmosphere. Used fluxes were H_3BO_3, LiF, CaF_2 and NH_4Cl. Also, a sample without flux was investigated. Firing without flux showed no x-ray diffraction peaks close to CSS silicate garnet. The dependence of different fluxes on photoluminescence properties was also in-vestigated It was shown that in terms of luminescence intensity CaF2 shows the best result.

A white LED was produced with the CSS phosphor synthesized at 1350°C with 1 wt% CaF_2. The color correlated temperature (CCT) was determined to 4872 K and is therefore by about 1500 K lower than in common WLEDs with YAG:Ce. Moreover, the color rendering index (CRI) was estimated to be 84.0, also exceeding the CRI properties of commercial WLEDs with YAG:Ce.

Liu et al. produced CSS doped with cerium via sol gel combustion method in 2009 and compared the general and optical properties of these samples with samples produced

Innovative architecture design for high performance organic and hybrid multi-junction solar cells

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ABSTRACT

The multi-junction concept is especially attractive for the photovoltaic (PV) research community owing to its potential to overcome the Schockley-Queisser limit of single-junction solar cells. Tremendous research interests are now focused on the development of high-performance absorbers and novel device architectures for emerging PV technologies, such as organic and perovskite PVs. It has been predicted that the multi-junction concept is able to boost the organic and perovskite PV technologies approaching the 20% and 30% benchmarks, respectively, showing a bright future of commercialization of the emerging PV technologies. In this contribution, we will demonstrate innovative architecture design for solution-processed, highly functional organic and hybrid multi-junction solar cells. A simple but elegant approach to fabricating organic and hybrid multi-junction solar cells will be introduced. By laminating single organic/hybrid solar cells together through an intermediate layer, the manufacturing cost and complexity of large-scale multi-junction solar cells can be significantly reduced. This smart approach to balancing the photocurrents as well as open circuit voltages in multi-junction solar cells will be demonstrated and discussed in detail.

Keywords: organic photovoltaics, perovskite solar cells, hybrid solar cells, multi-junction concept, tandem solar cells, lamination, innovative architecture design

1. INTRODUCTION

As we move through the Information Age, the world faces important challenges resulting from energy demand growth and a rising population. 17% of the world's global population or 1.2 billion people lack access to electricity. Low-cost photovoltaics is one key technology capable of mitigating technological and social inequality. Thin-film organic (OPVs) and hybrid perovskite solar cells are considered promising candidates for sustainable energy production with short energy payback times because they can be processed from solution and deployed on a massive scale while providing excellent form factors and competitive power conversion efficiencies (PCEs).[1-5] Given the prognosis that the cost of a final product based on thin-film photovoltaics is mainly determined by the cost associated with the fabrication and packaging rather than material-related costs, innovation in affordable and reliable large-scale fabrication techniques is imperative.[6]

Owing to their novel properties, practical applicability and low-cost large-scale manufacturing process, OPVs have attracted tremendous attention from researchers in the last decade.[7-24] The PCEs of single-junction OPV devices have been continuously improved to >11% and are expected to approach the 15% theoretical limit as a result of designing and developing novel absorbing materials with reduced bandgap-voltage offset along with high fill factor (FF) and external quantum efficiency (EQE).[25-31] Compared to their inorganic counterparts, the relatively narrow absorption windows of the organic absorbers inevitably restrict the utilization of photons, thus limiting their performances.

The tandem architecture, in which two or more sub-cells with complementary absorption spectra are monolithically stacked together and connected in series, has been proven to be one of the most promising concepts to address the losses related to the narrow absorption of organic absorbers.[32, 33] The loss due to thermalization of the excess energy photons can also be simultaneously minimized by combining absorbers possessing different bandgaps in a tandem architecture. The high-energy photons can be absorbed in a front-placed wide bandgap donor to deliver a high open circuit voltage (V_{OC}), whereas the photons with energies lower than the bandgap of the front absorber can be absorbed by the back-

Organic, Hybrid, and Perovskite Photovoltaics XVIII, edited by Zakya H. Kafafi, Paul A. Lane, Kwanghee Lee, Proc. of SPIE Vol. 10363, 103631K · © 2017 SPIE
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2271629

PHOSPHOR PARTICLES FOR LUMINESCENT DOWN-SHIFTING IN PHOTOVOLTAICS: DETERMINATION OF COMPLEX REFRACTIVE INDICES

Benjamin Lipovšek[1], Anastasiia Solodovnyk[2,3], Daniel Riedel[3], Andres Osvet[3], Jessica Gast[2], Edda Stern[2], Karen Forberich[3], Miroslaw Batentschuk[3], Christoph J. Barbec[2,3], Janez Krč[1], and Marko Topič[1]
[1] University of Ljubljana, Faculty of Electrical Engineering, Tržaška 25, 1000 Ljubljana, Slovenia
[2] Bavarian Center for Applied Energy Research (ZAE Bayern), Haberstr. 2a, 91058 Erlangen, Germany
[3] Friedrich-Alexander University Erlangen-Nürnberg (FAU), Martensstr. 7, 91058 Erlangen, Germany

ABSTRACT: We demonstrate a novel two-step method for accurate determination of the complex refractive indices of phosphor materials in particulate form. The real part of the refractive index is first measured at a number of selected wavelengths using the Becke Line method; the results are interpolated over a broader wavelength range using Sellmeier's equations. The imaginary part of the refractive index is extracted from measured optical characteristics of polymer layers embedded with phosphor particles; a specialized numerical simulation tool is employed for this purpose. Finally, using the determined complex refractive indices, we numerically investigate the potential of luminescent down-shifting applied to thin-film solution-processed solar cells. We study the influence of the main properties of luminescent down-shifting layers filled with phosphor particles, and indicate the gains in the solar cell performance that can be obtained using this approach.

Keywords: Modelling, Optical Properties, Organic Solar Cell, Photoluminescence, Photovoltaic

1 INTRODUCTION

To improve the conversion efficiency of single-junction solar cells in the short-wavelength region, the concept of luminescent down-shifting (LDS) can be applied [1–4]. This approach is based on the application of photoluminescent (PL) materials that shift the UV and near-UV photons to photons of longer wavelengths where the spectral response of the solar cell is much higher. Among different types of PL materials, phosphor particles show many advantages such as large Stokes shift, high PL quantum yield, and long-term stability [5, 6]. Dispersed in a transparent polymer binder, they can be easily deposited on top of the solar cell in form of an LDS layer [7]. However, due to the relatively large size of phosphor particles (from a few microns to a few tens of microns), scattering at these particles inside the LDS layer can lead to a reduced overall transmission of the incident light into the underlying solar cell [7,8]. Therefore, detailed analysis and careful optimization of the LDS layer composition is required (i.e. the layer thickness, the volume concentration of the phosphor particles, and the size distribution of the phosphor particles), which can be done efficiently using an appropriate optical modelling and simulation tool [9].

The accuracy of numerical simulations, however, depends heavily on the accuracy of the input parameters. In terms of optical simulations of phosphor-based LDS layers, as well as complete solar cells enhanced with such LDS layers, we experienced that the complex refractive indices of the phosphor particles present the most critical input parameter. They are mostly unknown, and, due to the particulate form of the phosphor material, they are also notoriously difficult to determine using the conventional measurement techniques (e.g. ellipsometry).

In this work, we first demonstrate the application of a novel method to precisely determine the wavelength-dependent complex refractive indices ($n(\lambda) - i \cdot k(\lambda)$) of different kinds of particulate phosphor materials [10]. The method consists of two steps that enable seperate determination of the real part, n, and the imaginary part, k (extinction coefficient), of the complex refractive index. Then, using the determined complex refractive indices, we also present the results of complete optical simulations of example solution-processed organic solar cells enhanced with luminescent down-shifting phosphor-filled layers. We investigate the potential of the LDS layers for improved solar spectrum harvesting in these devices, and discuss the optimal parameters of the LDS layers that would be most appropriate for this application.

2 *n* & *k* DETERMINATION METHOD

A number of different phosphor materials were included in our study, all of which existed in particulate (powder) form with particle sizes ranging from 10 µm to 20 µm (the precise particle size distributions have been determined experimentally [7]): (i) $Lu_3Al_5O_{12}:Ce^{3+}$, (ii) $Ba_2SiO_4:Eu^{2+}$, (iii) $Ba_3MgSi_2O_8:Eu^{2+},Mn^{2+}$, and (iv) $SrAl_2O_4:Eu^{2+}$. All of these phosphor materials absorb at short wavelenghts (< 500 nm) and emit at longer wavelenghts of the visible spectrum. Example photoluminescence excitation / emission spectra for $Lu_3Al_5O_{12}:Ce^{3+}$ are presented in Fig. 1, together with the SEM image of the phosphor particles.

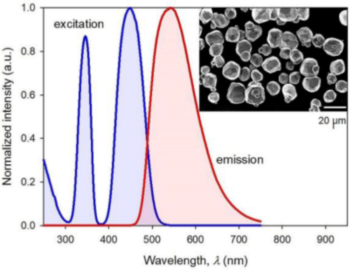

Figure 1: Photoluminescence excitation and emission spectra of $Lu_3Al_5O_{12}:Ce^{3+}$ phopsphor particles. The SEM image of the particles is shown in the inset.

Novel fatty-acid assisted co-precipitation method for the synthesis of $SrAl_2O_4$:Eu^{2+}, Sm^{3+} storage phosphor nanoparticles

Lukas Römling, Ievgen Levchuk, Max Steimle, Andres Osvet, Miroslaw Batentschuk
(miroslaw.batentschuk@fau.de), Albrecht Winnacker and Christoph J. Brabec

Friedrich-Alexander University Erlangen-Nürnberg, Department of Materials Science, Institute of
Materials for Electronics and Energy Technology

ABSTRACT

In this work $SrAl_2O_4$ doped with Eu^{2+} and Sm^{3+} were successfully synthesized using a novel fatty acid assisted co-precipitation method. The main focus was laid on (1) finding a suitable synthesis procedure to reproducibly obtain nanosized $SrAl_2O_4$ doped with Europium and Samarium of high purity (2) optimizing the Eu^{2+} concentration for nano scaled Strontium Aluminate and finally (3) optimizing the co-doping amount of Sm^{3+} to obtain a high intensity photostimulated luminesence (PSL). As a last step the dependence of the PSL signal to the write-in and read-out wavelengths of the stimulating light was determined.

Keywords: $SrAl_2O_4$, phosphor, photostimulated luminescence, co-precipitation,

1 INTRODUCTION

Optical imaging is a steadily developing field of medical diagnostics, which provides more cost efficient and harmless to the patient as well as an simpler setup – superior to other imaging techniques like microCT, ultraound or positron emission tomography. However, optical imaging is still limited by some factors.

When organic tissue is irradiated with blue or UV light it exhibits autofluorescence, which hinders the detection of biomarkers based on luminescence. Thus using conventional luminescence is limited to surface near imaging.

Using materials that show a long afterglow can bypass the problem of organic autofluorescence. By irradiating the phosphor particles prior to injection the phosphorescence (PP) can still be detected in the organic tissue without simultanious stimulation with UV light. For this method the time of afterglow is the limiting factor

Photostimulated luminescence occurs due to trapping the charge carriers in deep traps in the material.

Those electrons can be freed by stimulating with long wavelength light, not able to excite the autofluorescence, enabling the background-free detection of luminescence .

Another important issue is cytotoxicity. Core-shell particles that are or are proposed to be used for photoluminescence imaging often contain elements Se, Cd, Zn, Te, Hg and Pb.[1] Rare-earth-doped oxide particles have the potential to provide nontoxic water-stable photostimulable markers .

In recent years strontium aluminates doped with Europium and other rare earth ions, have gained more and more interest. In 2013 Dong et al. reported that the photostimulated luminescence intensity and the storage capacity of $Sr_3Al_2O_5Cl_2$:Eu^{2+} could be enhanced by factors of 441 and 91 respectively by co-doping the aluminate with Tm^{3+}. Dong et al. used the commonly used solid state reaction to synthesize the phosphor. After irradiating the phosphor with UV or blue light the sample exhibited PSL after stimulation. [2] In 2015 Manashirov et al. expanded this research and reported a new strontium-aluminate based phosphor that showed long persistent photostimulated luminescence afterglow. By triple doping $Sr_4(Al,B)_{14}O_{25}$:Eu^{2+},Tm^{3+} with Er^{3+} the long lasting spontaneous luminescence (LLSL) as well as the persistent photostimulated luminescence afterglow (PPSLA) increased by 100%. However, it has to be mentioned that the intensity of the PSL does decrease with increasing afterglow time. They concluded that the addition of Er^{3+} as a third dopant would change the ratio of deep traps and shallow traps. With Er^{3+} doping, the amount of shallow traps increases while the amount of deep traps is reduced. This results in a weaker PSL intensity but a longer afterglow since the process is supposed to involve de-trapping of charge carriers and re-trapping in more shallow traps. [3] The $SrAl_2O_4$ system doped with Eu^{2+} and Dy^{3+} is the most investigated aluminate owing to the excellent PP.

In 2016 Liu et al. also reported photostimulated luminescence by stimulating the phosphor with near infrared (NIR) light at 760 nm. From thermoluminescence measurements and also from previous reports from other research teams they concluded that there must be deep traps that are stable at room temperature which leads to PSL. The phosphor´s storage capacity is high and due to retrapping between a distribution of traps it could be stimulated by NIR light multiple times with the same PSL intensity, after only one charging process.[4] It can be seen that strontium aluminates are very promising for potential application as marker materials. However, the previously mentioned advances on strontium aluminates were all made on the micrometer scale. The task at hand is to find a reliable way to synthesise nanosized strontium aluminate with excellent performance.

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Energy Procedia

www.elsevier.com/locate/procedia

7th International Conference on Silicon Photovoltaics, SiliconPV 2017

Comparison of Drone-based IR-imaging with Module Resolved Monitoring Power Data

Janine Teubner[a,]*, Ingmar Kruse[b], Hans Scheuerpflug[a], Claudia Buerhop-Lutz[a], Jens Hauch[a], Christian Camus[a], Christoph J. Brabec[c,a]

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[b]*SunSniffer GmbH & Co. KG, Ludwig-Feuerbach-Straße 69, Nuremberg 90489, Germany*
[c]*Institute Materials for Electronics and Energy Technology, Martenstraße 7, Erlangen 91058, Germany*

Abstract

Two testing methods for photovoltaic (PV) plants, an infrared (IR)-measurement aerial system and a monitoring system on module level, are compared with respect to their capabilities for identifying irregularities of PV panels in a PV plant.

For the first method, a hypothesis is tested that infrared temperature and module power can be correlated with an empirical linear correlation using the raw measurement data of the second method. A workaround is proposed how to quantify power losses for unknown PV plants showing at the same time how power losses depend on ambient conditions. Also, the data is used to improve results from the IR-measurements. The second method is explained to compare the two methods. It is shown that each method offers different advantages, helping to properly assess and schedule O&M measures.

Peer review by the scientific conference committee of SiliconPV 2017 under responsibility of PSE AG.

Keywords: IR thermography; UAV; inspection; silicon photovoltaics; reliability; power loss correlation

1. Introduction

In the past years, reliability and maintenance of solar power plants have seen growing interest. The importance of quality inspection lays in the impact which defective photovoltaic (PV) modules can have on power output as well

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8. Books & Book Chapters

Tayebeh Ameri, Michael Forster, Ullrich Scherf, Christoph J. Brabec
Elementary Processes in Organic Photovoltaics
Near-Infrared Sensitization of Polymer/Fullerene Solar Cells: Controlling the Morphology and Transport in Ternary Blends
Edited by Karl Leo, Springer, Volume 272 of the series Advances in Polymer Science pp. 311-326, Oline December 2016, Print 2017
Print ISBN: 978-3-319-28336-4, Online ISBN: 978-3-319-28338-8
DOI: 10.1007/978-3-319-28338-8_13

Jose Dario Perea Ospina, Stefan Langner, Tayebeh Ameri and Christoph J. Brabec
Encyclopedia of Physical Organic Chemistry, 6 Volume Set, Band 1
Solubility and miscibility for diluted polymers and their extension to organic semiconductors
Edited by Zerong Wang, John Wiley & Sons, 6 *Volume Set, Band 1 pp. 697-735, April 2017*
Print ISBN: 99781118470459
DOI: 10.1002/9781118468586.epoc1028

Stubhan T., Wolf N., Manara J., Dyakonov V., Brabec C.J.
Elementary Processes in Organic Photovoltaics
Controlling the electronic interface properties in polymer–fullerene bulk heterojunction solar cells
Edited by Karl Leo, Springer, Volume 272 of the series Advances in Polymer Science pp. 311-326, Online December 2016, Print 2017
Print ISBN: 978-3-319-28336-4, Online ISBN: 978-3-319-28338-8
DOI: 10.1007/978-3-319-28338-8_12

Elementary Processes in Organic Photovoltaics
Volume 272 of the series Advances in Polymer Science pp. 311-326

Near-Infrared Sensitization of Polymer/Fullerene Solar Cells: Controlling the Morphology and Transport in Ternary Blends

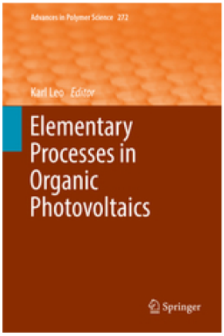
Tayebeh Ameri, Michael Forster, Ullrich Scherf, Christoph J. Brabec

Contents

Abstract

The concept of near-infrared (NIR) sensitization can be used as an alternative strategy to extend the spectral sensitivity of wide-bandgap polymers in polymer/fullerene solar cells. In ternary systems consisting of a conjugated polymer donor, a fullerene acceptor, and a sensitizer, the fullerene needs to act as an electron acceptor as well as an electron-transport matrix, the polymeric donor should provide a sufficiently high hole mobility, and the sensitizers should sensitize the bulk heterojunction solar cell in the red/NIR region. So far we have used various optoelectrical and structural techniques to investigate the possible mechanisms of the charge transfer and charge transport among the three components and microstructure of the ternary blends. In this review-like chapter, we present our recent achievements on developing the concept of NIR sensitization for polymer/fullerene solar cells by mainly addressing the important aspect of the relationship between morphology and transport.

Keywords
Cascade alignment Differential scanning calorimetry Fullerene multiadducts GIWAXS Hansen solubility parameters Morphology agent Near-IR sensitization OPV Phase diagram SCLC Surface energy Ternary solar cell Time-resolved pump-probe spectroscopy Transport.



SOLUBILITY AND MISCIBILITY FOR DILUTED POLYMERS AND THEIR EXTENSION TO ORGANIC SEMICONDUCTORS

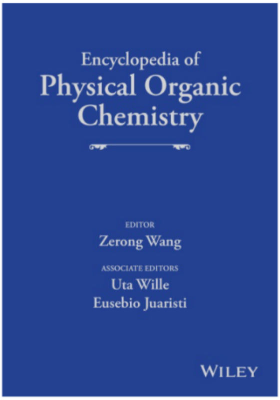
Jose Dario Perea Ospina, Stefan Langner, Tayebeh Ameri, and Christoph J. Brabec

Institute of Materials for Electronics and Energy Technology (i-MEET), Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany

1 INTRODUCTION

Nowadays, the necessity to design customized solvents for the optimization of chemical processes in industry and laboratory research has significantly increased, requiring better measures, faster simulation techniques, and more precise predictions. Organic semiconductors are one of the most challenging material systems for the design of suitable solvent systems. Due to their easy processability from solution, mechanical flexibility, and low costs, organic semiconductors have found wide applications in industry, and their performances have been continuously improved by means of research and development. While organic light emitting diodes (OLEDs) have advanced to a main stream application [1], other electronic applications such as transistors and solar cells have just been introduced into the market. Among these applications, the rather novel concept of bulk heterojunction organic solar cells (BHJ-OSC) [2, 3] is more challenging in terms of the formation of microstructure as a function of solubility and miscibility of various components. Both solubility and miscibility of organic compounds in solvents play equally important roles in chemistry and energy technology, such as in the case of ink formulation for optimized printing and drying processes and ultimately for the formation of microstructure and film. Solubility, as a description of the ability of a substance to dissolve in a particular solvent, is the fundament toward designing inks and solvent systems with mutual multicomponent solubility regimes [4]. However, the limited miscibility of the solution processed, polymorphism, formation of solvate of solid, and so on make the prediction of solubility difficult.

Encyclopedia of Physical Organic Chemistry, First Edition. Edited by Zerong Wang.
ISBN 978-1-118-46858-6.



Elementary Processes in Organic Photovoltaics
Volume 272 of the series Advances in Polymer Science pp. 293-310
DOI: 10.1007/978-3-319-28338-8_12

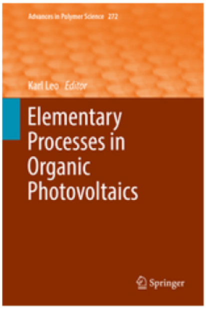
Controlling the Electronic Interface Properties in Polymer–Fullerene Bulk Heterojunction Solar Cells

T. Stubhan, N.Wolf, J. Manara, V. Dyakonov, and C.J. Brabec

Contents

Abstract This work covers the use of solution-processed metal oxides as interface layers for organic solar cells. To study the interface properties, intrinsic and Al-doped ZnO_x were chosen as reference systems. From the class of n-type metal oxides, ZnO_x was chosen because it can be doped when it is solution processed.

Keywords:
Aluminum-doped zinc oxide Barium hydroxide Charge transport in nanoparticular films Conjugated polyelectrolyte Device structure Diketopyrrolopyrrole-quinquethiophene Doped zinc oxide Electronic surface properties Energy diagram Energy-level diagrams EQE spectra Inferface layers for organic solar cells Interface layers Interface modification layers Inverted organic solar cells J-V characteristics Low temperature Molybdenum oxide Mott–Schottky capacitance Oxygen P3HT PCDTBT Phosphonic acid anchored fullerene SAM Polyvinylpyrrolidone Poole–Frenkel effect Reference solar cells SAM modification Stability of interface materials Stabilization of AZO nanoparticles Summary Thickness dependence Trioxadecanoic acid Water Zinc oxide.



9. Presentations at Conferences, Workshops, Events

Ameri, Tayebeh

17. – 18.07.2017
2nd International Conference on Power and Energy Engineering, Munich, germany
Invited talk: *Ternary sensitization of organic solar cells: A multifunctional concept to boost power conversion efficiency*

18. – 21.09.2017
E-MRS Fall Meeting, Warsaw, Poland
Talk: *High-Performance Near-IR Sensitized Organic Solar Cells with Thick Active Layer Exceeding 11% Efficiency*

29.11.2017
University of Southern California, Los Angeles, USA
Talk: *Near IR sensitization of polymer/fullerene solar cells; a multifunctional concept to boost PCE*

04. – 07.12.2017
Next Generation Solar Energy Conference, Cali, Colombia
Invited talk: *Design, Development and Understanding of Ternary Sensitization Concept in Organic Photovoltaics*

Arzig, Matthias

18.09.2017
International Conference on Silicon Carbide and Related Materials (ICSCRM), Washington, USA
Talk: *Growth Conditions and In Situ Computed Tomography Analysis of Facetted Bulk Growth of SiC Boules*

Batentschuk, Miroslaw

14. – 17.05.2017
TechConnect World Innovation Conference & Expo, Washington DC, USA
Talk: *Highly luminescent* $Ca_3Sc_2Si_3O_{12}:Ce^{3+}$ *silicate garnet nano- and microparticles with 50-70% photoluminescence quantum yields as efficient phosphor converters for white LEDs*

Brabec, Christoph J.

09.02.2017
Harvard University, Cambridge, Massachusetts, USA
Invited talk: *Challenges and Opportunities for High Throughput Material & Processing in Emerging Photovoltaics*

17.03.2017
Wissenschaftlicher Beirat des EnCN – MATSOL, Nuremberg, Germany
Talk: *Materialien für die Energiekonversion & Die Solarfabrik der Zukunft*

29. – 30.03.2017
International Exhibition and Conference for the Printed Electronic Industry, LOPEC, Munic, Germany
Invited Lecture and Course: *From Lab to Fab: Printed Photovoltaics*

10. – 11.07.2017
First Ulm-Erlangen Mini-Symposium Functional Organic Materials 2017, University of Ulm, Ulm, Germany
Invited talk: *Molecular Non Fullerene Acceptors for Organic Solar Cells: Photophysics, Performance and Lifetime in Comparison to Fullerenes*

03.08.2017
CLEO Pacific Rim Conference, Singapore, Singapore
Key Note Speech: *Hystersis in Perovksite Solar cells*

04.08.2017
Nanyang Technological University, Singapore, Singapore
Invited talk: *Transport Physics of Non Fullerene Acceptors*

19.09.2017
3rd International Conference on Perovskite Solar Cells and Optoelectronics (PSCO17), Oxford, United Kingdom
Invited: *Overcoming Hystersis in Perovksite Solar Cells*

24. – 26.09.2017
Fourth Erlangen Symposium on Synthetic Carbon Allotropes 2017, Erlangen, Germany
Invited talk: *Molecular Acceptors for Photovoltaics*

27.09.2017
Reichsuniversität Groningen, Groningen, Netherlands
Talk: *High Throughput Processing of Opto-Electronic Devices*

02.10.2017
Workshop RECENDT, Bad Mitterndorf, Austria
Invited talk: *Strategy and R&D Innovation for SMEs*

16.10.2017
Hong Kong University of Science and Technology, Hongkong, China
Key Note Speech: *The Role of Miscibility on Microstructure Instabilities in Bulk Heterojunction Composites*

17.10.2017
South China University of Technology, Guangzhou, China
Invited talk: *Highthroughput Approaches in organic semiconductor science*

19.10.2017
Wuhan University, Wuhan, China
Invited talk: *Non Fullerene Acceptors – a path towards 15 % organic solar cells*

20.10.2017
Chinese Academy of Sciences, Beijing, China
Invited talk: *Highthroughput Engineering of functional materials*

08.11.2017
Max-Planck-Institut für molekulare Pflanzenphysiologie, Wissenschaftspark Golm, Potsdam, Germany
Invited talk: *The Photophysics of Non Fullerene Acceptors: Transport, Devices and Environmental Stability*

17.11.2017
Forschungszentrum Jülich, Wissenschaftlicher Technischer Beirat, Jülich, Germany
Invited talk: *PV for the Terrawatt Era*

23.11.2017
Beilstein Nanotechnology Symposium, Berlin, Germany
Invited talk: *Perovskite tandem cells: advanced interface engineering for 4T and 2T concepts with high performance*

06.12.2017
Next Generation Solar Energy, Cali, Colombia
Keynote Speech: *The Mateirals Genome Challenge – Miscibility, Microstructure Instabilities and Bulk Heterojunction Composites*

Chepyga, Liudmyla

27.08. – 01.09.2017
18th International Conference on Luminescence, João Pessoa, Paraíba State-Brazil
Talk: *New silicate based thermographic phosphors and its photoluminescence properties: Dy doped* Y_2SiO_5 *and* $Ca_3Sc_2Si_3O_{12}$

Gu, Ening

02. – 05.07.2017
NEXT-GEN III: Photovoltaics MATERIALS, Groningen, Netherlands
Poster: *Synthesis and characterizations of* $AgBiS_2$ *thin films based on a low temperature molecular ink*

He, Yakun

02. – 05.07.2017
NEXT-GEN III: Photovoltaics MATERIALS, Groningen, Netherlands

Heinrichsdobler, Armin

06. – 10.08.2017
Conference SPIE Optics & Photonics 2017, San Diego, California, United States
Paper : *Inkjet-printed polymer-based scattering layers for enhanced light out coupling from top-emitting organic light-emitting diodes*

Heiss, Wolfgang

03. – 07.07.2017
Nanoscience with nanocrystals, Braga, Portugal
Invited Talk: *Hydrogen Bonded Organic Pigment Colloidal Nanocrystals*

Hepp, Johannes

25. – 29.09.2017
33rd European Photovoltaic Solar Energy Conference and Exhibition,
Amsterdam, Netherlands
Talk: *Separating the influence of material composition and local defects on the* V_{oc} *of CIGS solar modules*

15. – 17.11.2017
8th International Conference and Exhibition on Lasers, Optics & Photonics,
Las Vegas, USA
Invited Talk: *Automatized optical quality assessment of photovoltaic modules*

Kahmann, Simon

17. – 18.01.2017
Physics @ Veldhoven, Veldhoven, Netherlands

19. – 23.01.2017
12th Conference of Optical Probes on Organic and Hybrid Semiconductors, Quebec, Canada
Talk: *Excited state interaction in polymer wrapped single walled carbon nanotubes*

02. – 05.07.2017
Next Generation III: Photovoltaics Materials, Groningen, The Netherlands
Talk: *Trap states in lead sulphide colloidal quantum dots investigated via photoinduced absorption spectroscopy*

Langner, Stefan

05. – 07.04.2017
HSP50- Fifty Years of Hansen Solubility Parameters, University of York, York, England
Invited Talk, Keynote Speech: *HSP for Smart Formulations of Organic Semiconductor-Inks*

21. – 24.05.2017
International Conference on Hybrid and Organic Photovoltaics (HOPV 17), Lausanne, Switzerland
Talk: *Organic solar cells processed from environmentally friendly solvent blends*

10.11.2017
Sonderforschungsbereich 953 (SFB 953) Seminar, Erlangen, Germany
Talk: *Microstructure Instabilities in Polymer-Fullerene Composites*

Levchuk, Ievgen

02. – 05.07.2017
Next-Gen III: Photovoltaics Materials Conference, Groningen, Netherlands
Poster: *Perovskite ink: from nanocrystals design to device application*

18. – 20.09.2017
3rd International Conference on Perovskite Solar Cells and Optoelectronics (PSCO17), Oxford, United Kingdom
Talk: *Perovskite ink: from nanocrystals design to device application*

Li, Ning

13. – 15.03.2017
Workshop: i-MEET/ZAE Winter School, Lam, Germany
Talk: *Tandem am i-MEET*

16. -17.05.2017
The Second International Young Scientist Forum on Frontiers in Materials Science and Engineering, Tongji University, Shanghai, China
Invited Talk: *Organic Photovoltaics and Printed Organic Tandem Solar Cells*

18.05.2017
Ningbo Institute of Industrial Technology, Chinese Academy of Science, Ningbo, China
Invited Talk: *Assessing the potential of high-performance donor materials for multi-junction applications*

28. – 30.05.2017
1st Workshop of the DFG-NSFC collaborative project “NovPolSol”, i-MEET, Erlangen, Germany
Invited Talk: *Research Activities at the i-MEET, FAU*

04. – 08.06.2017
13th International Conference on Organic Electronics 2017, Saint Petersburg, Russia
Talk: *Solution-processed organic tandem solar cells: design, optimization and loss analysis*

02. – 05.07.2017
Next Generation III: Photovoltaics Materials, Groningen, The Netherlands
Talk: *Towards large-scale solution processing of tandem solar cells: assessing the potential of high performance polymer donors for multi-junction applications*

17. – 20.07.2017
15th European Conference on Organized Films, Dresden, Germany
Invited Talk: *Microstructure instabilities in polymer-fullerene thin films for photovoltaic applications*

06. – 10.08.2017
Conference SPIE Optics & Photonics 2017, San Diego, California, United States
Talk: *Innovative architecture design for high performance organic and hybrid multi-junction solar cells*

27.08. – 01.09.2017
The 15th International Conference on Advanced Materials IUMRS-ICAM 2017, Kyoto, Japan
Talk: *Abnormal strong burn-in degradation in solution-processed organic bulk-heterojunction solar cells*
Talk: *Degradation of highly efficient organic bulk-heterojunction solar cells caused by spinodal donor-acceptor demixing*

09.10.2017
Workshop: i-MEET/ZAE Fall Meeting, Kainsbach – Happurg, Germany
Talk: *Tandem Photovoltaics*

10. – 12.10.2017
International Congress Engineering of Advanced Materials (ICEAM 2017), Erlangen, Germany
Invited Keynote Talk: *Morphology of organic solar cells*

16. – 18.10.2017
2nd Workshop of the DFG-NSFC collaborative project “NovPolSol”, SCUT, Guangzhou, China
Talk: *Burn-in degradation of solution-processed polymer:fullerene solar cells*

23.10.2017
HEEGER Beijing Research and Development Center, Beihang University, Beijing, China
Invited Talk: *Burn-in degradation of highly efficient polymer solar cells*

24.10.2017
Location: New Materials Technology Academe, University of Science and Technology Beijing, China
Invited Talk: *Microstructure instabilities in solution-processed polymer-fullerene solar cells*

26. – 28.12.2017
East Lake International Forum for Outstanding Overseas Young Scholars
Huazhong University of Science and Technology, Wuhan, China
Invited Talk: *Microstructure instabilities in solution-processed organic bulk-heterojunction solar cells*

28.12.2017
School of Physics and Technology, Wuhan University, Wuhan, China
Invited Talk: *Microstructure instabilities in solution-processed organic bulk-heterojunction solar cells*

Perea Ospina, Jose Dario

01.05. – 04.11.2017
Harvard University, Course Tester: The Quantum World EDx, Professor Alan Aspuru Guzik, Cambridge, Massachusetts, USA

20.07.2017 Invited talk: *Organic Photovoltaics: Fundamentals, Materials and Processing*

01.11.2017 MIT, Invited talk: *Predicting the Microstructure Stability in Photovoltaic Polymer-Fullerene Blends Using Figure of Merit*

15.11.2017
Cauca University, Popayan, Colombia
Invited talk: *Organic Photovoltaics: Fundamentals, Materials and Processing*

17.11.2017
Valle University, Cali, Colombia
Invited talk: *Organic Photovoltaics: Fundamentals, Materials and Processing*

04. – 07.12.2017
Next Generation Solar Energy 2017, Cali, Colombia
Invited talk: *The Role of Miscibility on Microstructure Instabilities in Bulk Heterojunction Composites*
Contribution: *Predicting the Microstructure Stability in Photovoltaic Polymer-Fullerene Blends Using Figure of Merit*

14. – 17.12.2017
KADA-2017-Colombia, Pereira, Colombia
Invited talk: *A brief overview of the solars cells in Colombia*

Schimmel, Saskia

08. – 10.03.2017
5th German Swiss Conference on Crystal Growth GSCCG-5/DKT 2017, Freiburg, Germany
Poster: *Chemical stability of carbon-based inorganic construction materials for in situ x-ray measurements of ammonothermal crystal growth of nitrides*

18. – 22.09.2017
10th International Workshop on Bulk Nitride Semiconductors (IWBNS-X), Nuuksio National Park, Espoo, Finland
Talk: *Insights into the ammonothermal growth process of GaN by in situ x-ray visualization*

11. – 12.10.2017
DGKK-AK „Massive Halbleiterkristalle“, TU Bergakademie Freiberg, Freiberg, Germany
Talk: *Insights into ammonothermal growth of nitrides by in situ measurement techniques*

Schöler, Michael

22. – 26.05.2017
European Materials Research Society (EMRS) Spring Meeting, Strasbourg Convention Centre, Strasbourg, France
Talk: *Characterization of defects in 3C-SiC grown by Sublimation Epitaxy using 3C-SiC-on-Si templates*

14. – 15.09.2017
The 5th International Workshop on LEDs and Solar Applications, DTU Technical University of Denmark, Copenhagen, Denmark
Talk: *Evaluation of defects in 3C-SiC grown by Sublimation Epitaxy using 3C-SiC-on-Si seeding layers*

11. – 12.10.2017
DGKK-AK „Massive Halbleiterkristalle“, TU Bergakademie Freiberg, Freiberg, Germany
Talk: *Evaluation of defects in 3C-SiC grown by Sublimation Epitaxy using 3C-SiC-on-Si seeding layers*

Shrestha, Shreetu

02. – 05.07.2017
Next Generation III: Photovoltaics Materials, Groningen, The Netherlands
Poster presentation: *Temperature dependent and ambipolar time of flight mobility of perovskite single crystals*

18. – 20.09.2017
3rd International Conference on Perovskite Solar Cells and Optoelectronics (PSCO17), Oxford, United Kingdom
Talk: *Temperature dependent time of flight mobility measurements on* $MAPbI_3$ *single crystals*

Winnacker, Albrecht

14. – 17.05.2017
TechConnect World Innovation Conference & Expo, Washington DC, USA
Talk: *Novel fatty-acid assisted co-precipitation method for the synthesis of* $SrAl_2O_4$: Eu^{2+}, Sm^{3+} *storage phosphor nanoparticles*

Xie, Chen

02. – 05.07.2017
Next Generation III: Photovoltaics Materials, Groningen, The Netherlands

Zhang, Chaohong

02. – 05.07.2017
Next Generation III: Photovoltaics Materials, Groningen, The Netherlands
Poster presentation: *On the correlation of miscibility, stability and optoelectronic properties for polymer-fullerene solar cells*

10. Seminar Presentations

Chair Seminar

10.01.2017
Patrick Dreher (Master thesis report)
Detektion von Volumendefekten und Anbindungsfehlern in der Halbleiter-Substrat-Verbindung von leistungselektronischen Modulen - Ultraschallmikroskopie, Röntgen und Thermographie im Vergleich

17.01.2017
Andre Karl (Doctoral thesis report)
Imaging of artificially induced defects in OPV

24.01.2017
Sebastian Strohm (Master thesis report)
Bulk Heterojunction Solar Cells Based on P3HT and the Non-Fullerene Acceptor IDTBR

31.01.2017
Benjamin Sanchez (Guest talk, Harvard Green Project)
Exploring chemical space: high throughput screening for new materials

14.02.2017
Felix Schröppel (Master thesis report)
Synthesis of novel phosphors based on Cer3+ doped silicate garnets

Yi Hou (Doctoral thesis report)
A universal strategy to overcome the hole transporting limitations in perovskite solar cells

28.02.2017
Philipp Köder (Master thesis report)
Solution-Processes Interconnection Layers for Silicon-Perovsite Tandem Solar Cells

Armin Heinrichsdobler (Doctoral thesis report, Osram OLED GmbH.)
Inkjet-printed internal light extraction layers for top-emitting OLEDs

07.03.2017
Carsten Polzer (Master thesis report)
Synthesis and investigation of temperature dependent luminescence of phosphor blends for thermography in biological objects

21.03.2017
Johannes Hepp (Doctoral thesis report)
Combined analysis of material properties and defects

28.03.2017
Daniel Niesner (Postdoc, Columbia University)
Effects of spin-Orbit coupling in lead halide perovskites

David Czajkowski (Master thesis report)
Investigation of Silver Nanowire Inks Focused on their Suitability in Solar Cells

30.03.2017
Lukas Römling (Bachelor thesis report)
Novel fatty acid assisted approach for the synthesis of nanosized $SrAl_2O_4:Eu^{2+}$

04.04.2017
Michael Silba (Guest talk, EPFL Lausanne)
Multication, Highly Stable and Effienct Perovskite Solar Cells

Johannes Küffner (Master thesis report)
Transfer of room-temperature crystallized perovskite solar cells via solvent-solvent extraction from spin coating in controlled atmosphere to doctor blading in ambient conditions

11.04.2017
Daniel Cruz (MSc, Max Planck of Colloids and Interfaces)
Controlled synthesis of $g\text{-}C_3N_4$ *beyond of artificial photosynthesis: application on inorganic-organic perovskites*

25.04.2017
Josua Wachsmuth (Master thesis report)
Combinatorial Analysis of Organic Solar Cells with Non-Fullerene Electron Acceptors Using High-Throughput Methods

Kerstin Krebs
(Doctoral thesis report)
Transparent, conductive electrodes for touch panel displays

09.05.2017
Sri Paleti (Master thesis report)
The role of superoxide formation in photo-oxidation of bulk heterojunction blend films

23.05.2017
Marco Volleth (Bachelor thesis report)
Synthesis and Purification of Silver Nanowires for Transparent Electrodes

30.05.2017
Shreetu Shresta (Doctoral thesis report)
Transient photoconductivity measurements in $MAPbI_3$

13.06.2017
Dr. Qianqian Lin (Guest talk, University of Oxford)
Opto-electronics of perovskite solar cells and photodetector

20.06.2017
Shi Chen (Doctoral thesis report)
Robot synthesis and testing with a robot based high throughput approach

27.06.2017
Eric Tam (Doctoral thesis report)
Device structure for inkjet printed solar module

11.07.2017
César Omar Ramírez Quiroz (Doctoral thesis report)
All-solution 26.6% efficient silicon-perovskite tandem: balanced percolation in silver nanowire electrodes and optically coupled contacts

18.07.2017
Klaus Burlafinger (Doctoral thesis report)
Development of a high power illumination setup for accelerated photo-degradation of thin film solar cells

Haiwei Chen (Doctoral thesis report)
Stability of Perovskite Solar Cells

25.07.2017
Liudmyla Chepyga (Doctoral thesis report)
New silicate based thermographic phosphors and its photoluminescence properties: Dy doped $Y_2Si_2O_7$ *and* $Ca_3Sc_2Si_3O_{12}$

Eva Buchta (Bachelor thesis report)
Comparative long-term evaluation of different PV-technologies

Timo Wagner (Bachelor thesis report)
Technologyspecific evaluation of angle-dependent power measurement of PV modules

05.09.2017
Christoph Joisten (Master thesis report)
Accelerated degradation of organic solar cells

19.09.2017
Stefan Langner (Doctoral thesis report)
High throughput determination of solubility and HSP

26.09.2017
Marcel Marquart (Bachelor thesis)
Precise automated deposition of solution processed films using the liquid substrate method

Osbel Almora Rodríguez *(Doctoral thesis report)*
Capacitive and non-capacitive currents in perovskite solar cells

Dr. M. Batentschuk
Röntgenbelehrung

28.09.2017
Josua Wachsmuth (Talk)
Introduction in the simulation of solar cells

17.10.2017
Simon Kahmann (Doctoral thesis report)
Excited state interaction in networks of polychiral single walled carbon nanotubes with their wrapping polymers

Philipp Odenwald (Master thesis report)
Investigation on the X-Ray Sensitivity of Methyl-Ammonium Lead Iodide Wafer- and Single Crystal-Based Devices

Sebastian Kühner (Bachelor thesis report)
Temperaturabhängigkeit der Degradation von transparenten Silbernanodraht-Elektroden

24.10.2017
Tillman Böse (Bachelor thesis report)
Automatisierung von Strom-Spannungsmessungen an organischen Solarzellen

Leon Fraune (Bachelor thesis report)
Fabricating solution-processed organic solar cells on large substrates with a spincoater

14.11.2017
Chen Xie (Doctoral thesis report)
Water-alcohol processed nanoparticle OPV

Amjad Ali (Doctoral thesis report)
Luminescent materials for thermography

21.11.2017
José García Cerillo (Master thesis report)
Synthesis and characterization of TiO_2 *thin films doped with trivalent cations and their application into hybrid solar cells*

Jingming Cao (Master thesis report, MAOT Programm, Frauenhofer Inst. Mainz)
The characterization of materials properties by polarization-resolved time-domain terahertz spectroscopy

12.12.2017
Andrej Classen (Doctoral thesis report)
Update on Degradation Setup and Results

Junyi Xu (Master thesis report)
Thermally conductive polymer composites

19.12.2017
Prof. Hin-Lap Yip (South China University of Technology (SCUT))
Interface Design and Optical Management for Polymer and Perovskite Solar Cells

Guest Talks

31.01.2017
Benjamin Sanchez (Harvard Green Project)
Exploring chemical space: high throughput screening for new materials

28.03.2017
Daniel Niesner (Columbia University)
Effects of spin-Orbit coupling in lead halide perovskites

04.04.2017
Michael Silba (EPFL Lausanne)
Multication, Highly Stable and Effienct Perovskite Solar Cells

11.04.2017
Daniel Cruz (Max Planck of Colloids and Interfaces)
Controlled synthesis of g-C_3N_4 *beyond of artificial photosynthesis: application on inorganic-organic perovskites*

13.06.2017
Dr. Qianqian Lin (University of Oxford)
Opto-electronics of perovskite solar cells and photodetector

20.06.2017
Prof. Dr. Petro Fochuk (Chernivtsi National University, Ukraine)
Development and investigation of the semiconductor CdTe for electronics and solar energy

12.07.2017
Yicheng Zhao (University of Toronto)
Stability issues of perovskite solar cells

04.09.2017
Prof. Barry C. Thompson (Department of Chemistry, Loker Hydrocarbon Research Institute, University of Southern California)
The Influence of Polymer Structure on Ternary Blend Solar Cell Performance

04.10.2017
Dr. Christoph Lungenschmied (Trinamix GmbH., BASF)
Introducing Focus-Induced Photoresponse: A novel optical distance measurement technique using single-pixel photodetectors

07.11.2017
Dr. Günter Schmid (Siemens AG Corporate Technology Erlangen)
Direct Electrocatalytic Reduction of CO_2 *Toward CO and Hydrocarbons*

21.11.2017
Jingming Cao (MAOT Programm, Frauenhofer Inst. Mainz)
The characterization of materials properties by polarization-resolved time-domain terahertz spectroscopy

06.12.2017
Silvia Janietz (Fraunhofer Institute Applied Polymer Research)
From New Polymers up to a Pilot Line Processing of OPV at Fraunhofer IAP

12.12.2017
Loreleyn Flores (PUCP, Lima, Peru, Projekt DAAD-Concytec)
Luminescence properties of rare earth (Yb-Tb) co-doped amorphous $SiCxO_y$ *thin films*

19.12.2017
Prof. Hin-Lap Yip (South China University of Technology (SCUT))
Interface Design and Optical Management for Polymer and Perovskite Solar Cells

11. Conferences organized by Members of the Institute

Ameri, Tayebeh

17. – 21.09.2017
E-MRS 2017, Fall Meeting
Central Campus of Warsaw University of Technology, Warsaw, Poland
Committee member of symposium "NIR Optoelectronics – Organic Semiconductors and Devices"

Brabec, Christoph J.

04. – 07.12.2017
Next Generation Solar Energy
Universidad del Valle, Campus Ciudad Meléndez, Cali, Colombia
Organisation: Prof. Brabec, José Darío Perea Ospina

12. Cooperation in Committees

Ameri, Tayebeh

Associate Editor of Frontiers in Energy Research

Batentschuk, Miroslaw

Practica Commission of the Department of Material Science, Friedrich-Alexander University Erlangen-Nürnberg

Study Commission of the Department of Material Science, Friedrich-Alexander University Erlangen-Nürnberg

Brabec, Christoph J.

Mitarbeit am Forschungsnetzwerk des BMWi, Leitung der Fachgruppe Ökonomie, Metrologie und Charakterisierung

Serving as expert referee for European Community

Editor of *“Journal of Photonics for Energy”* (SPIE)

Chairman of the Editorial Board *“Advanced Energy Materials”*, Wiley VCH

Member of the Editorial Board of *“Progress in Photovoltaics”*, Wiley VCH

Member of the Editorial Board of *“Emerging Materials Research”*, ice publishing

Serving as referee for several funding organizations, among them the Austrian Science Fund (FWF), for the German Research Foundation (DFG), the Baden-Württemberg Stiftung, and for more than 15 top ranked journals

Serving as reviewer for multiple journals in the field of materials, semiconductors and energy (Nature Family, EES, Advanced Family)

Chairman of the Executive Board of the Bavarian Center for Applied Energy Research, ZAE Bayern, Würzburg

Scientific Director Department Renewable Energies, ZAE Bayern, Erlangen

EnCN – Deputy Spokesman, Member of the Academic Heads, Member of the Steering Committee, Nürnberg

EnCN e.V. – Member of the Board of Directors, Nürnberg

Spokesman of the Department of Material Science, Friedrich-Alexander University Erlangen-Nürnberg

Representative for the Material Science Department in the Board of the Technical Faculty of the FAU Erlangen-Nürnberg

Member of Scientific Board of the PE graduate school, Imperial College, London

Member of the Scientific Advising Board, CRANN AMBER, Trinity College Dublin, Ireland

Member of the Board of the "Kompetenznetzwerk Wasser und Energie Oberfranken-Ost e.V. ", Hof

Member of the Scientific Board of the International Conference on Organic Electronics (ICOE)

Member of the Board of the Next Generation Solar Energy Conference 2017, Cali, Columbia

Co-Organizer of the Congress series on Organic and Printed Photovoltaics, Erlangen and Würzburg

Principal Investigator of the Erlangen Cluster of Excellence *"Engineering of Advanced Materials" (EAM)*

Principal Investigator of the *"Solar Energy goes Hybrid"* Initative (SolTech) of the Bavarian State

Member of Graduate School in Advanced Optical Technologies (SOAT) Friedrich-Alexander-Universität Erlangen-Nürnberg

Collaborating PI of the CSC "111" Initative of the Heeger Center, Beijing, China

Principal Investigator of the CRC 953 "Carbon Allortopes", Friedrich-Alexander University Erlangen-Nürnberg

Principal Investigator of the GRK 1896 "in Situ Microscopy with Electroncs, X-Rays and Scanning Probes", Friedrich-Alexander University Erlangen-Nürnberg

Kahmann, Simon

Member of the Graduiertenkolleg GRK 1896

Wellmann, Peter

Member of the Exectuve Committee of the European Materials Research Society (EMRS).

Treasurer of the German Crystal Growth Association (DGKK e.V.)

13. Research Projects

Bayerische Forschungsstiftung, DOK-170-14 (Germany)
01.04.2014 – 31.03.2017
Entwicklung neuer Leuchtstoffe für die Hochtemperatur-Thermometrie

Cluster of Excellence Engineering of Advanced Materials (Forschungscluster „Engineering of Functional Material Interfaces“) EAM: FUMIN B
01.11.2017 – 31.12.2018
Energy harvefhing

COLCIENCIAS (Columbia)
01.11.2014 – 30.09.2018
(Perea Ospina, Jose Dario)

CONACYT (The Mexican National Council for Science and Technology) (Mexico)
01.08.2013 – 31.08.2018
(Ramirez Quiroz, César Omar)

China Scholarship Council (China)

CSC grant No. 201206130055
Design and Fabrication of organic solar cells based on solution-processed small molecules (Ke, Lili)

CSC grant:
Tang, Xiaofeng
Chen, Haiwei
Chen, Shi
Gu, Ening
He, Yakun
Liu, Chao
Xie, Chen
Zhang, Chaohong

Deutscher Akademischer Austauschdienst
Forschungsmobilität - Programme des Projektbezogenen Personenaustauschs
DAAD PPP Peru 2017 (Germany)
01.01.2017 – 31.12.2018
Herstellung und Charakterisierung von Up-/und Downkonvertern

Deutsche Forschungsgemeinschaft DFG: BR 4031/6-1 (Germany)
01.01.2016 – 31.12.2018
Entwicklung von neuen bildgebenden Verfahren zur Defekterkennung in Tandem Solarzellen

Deutsche Forschungsgemeinschaft DFG: BR 4031/9-1 (Germany)
01.01.2017 – 31.12.2018
Entwicklung einer innovativen Methode zur beschleunigten Bestimmung der Photo-Stabilität neuartiger Dünnfilm-Halbleitern zur Anwendung für Solarzellen

Deutsche Forschungsgemeinschaft DFG-NSFC: BR 4031/13-1 (Germany)
01.01.2017 – 31.12.2019
Development of novel organic semiconductors and advanced combinatorial characterization methods for high performance, printable polymer solar cells

Deutsche Forschungsgemeinschaft DFG WE 2107/6-2 (Germany)
01.01.2017 – 31.12.2018
In situ Visualisierung des ammonothermalen Kristallisationsprozesses mittels Röntgenmesstechnik

Deutsche Forschungsgemeinschaft DFG WE 2107/12-1 (Germany)
01.04.2016 – 30.04.2019
Analyse der Wachstumskinetik während der Hochtemperatur-Kristallzüchtung von SiC unter Anwendung der Computertomographie zur in-situ 3D Visualisierung der Wachstumsphasengrenze

Deutsches Zentrum für Luft- und Raumfahrt DLR: 01DJ16002 (Germany)
01.01.2016 – 30.06.2018
Einfach und doppelt dotierte mit Ce^{3+} *und* Eu^{2+} *nanokeramische Leuchtstoffe auf Silikat-Granat-Basis für weiße Hochleistungsleuchtdioden*

EnCN2 (Germany)
01.01.2017 – 31.12.2021
Erneuerbare EnergieträgerTechnologien im urbanen Umfeld (EET)
Speicher A

EU CHALLENGE 720827
01.01.2017 – 31.12.2020
3C-SiC Hetero-epitaxiALLy grown on silicon compliancE substrates and 3C-SiC substrates for sustaiNable wide-band-Gap powEr devices

Exzellenzcluster: B1 (Germany)
01.11.2012 – 31.10.2017
Printable solar cells

FUMIN bridge fund DFG (Germany)
01.11.2017 – 31.12.2018
Energy Materials

GRK1896 (Germany)
01.01.2014 – 31.03.2018
In-Situ Microscopy with Electrons, X-ray and Scanning Probes

HI-ERN Joint Projects Helmholtz-Institut Erlangen-Nürnberg (Germany)
01.01.2017 – 31.12.2018
Perovskite-based tandem solar cells

OSNIRO FP7-PEOPLE-2013-ITN (Germany)
01.10.2013 – 31.12.2017
Organic Semiconductors for NIR Optoelectronics

PHONSI (Germany)
2015 – 2018
Marie Skłodowska-Curie-Maßnahme Innovative Training Networks - ITN (Variante: European Training Network - ETN) im EU-Rahmenprogramm für Forschung und Innovation Horizont 2020

Projektträger Jülich 0324154D (Germany)
01.11.2017 – 30.09.2020
Verbundvorhaben: MYCIGS - Energieertragsoptimierte Cu (In,Ga)(S,Se)2-Dünnschichtsolarmodule durch gezielte Steuerung der Ertragsparameter; Teilvorhaben: Materialwissenschaftliche Charakterisierung

PV-ZUM DynoSol (BMWi) (Germany)
01.05.2017 – 30.04.2020

Real Nano (Germany)
2015 – 2017
FFG Programm Produktion der Zukunft

SFB 953 B01 (Germany)
01.01.2012 – 31.12.2019
Synthetic Carbon Allotropes

SolTech StMWFK (Germany)
25.07.2012 – 31.07.2017
Solar technologies go hybrid

SS16_Tech_01 (Germany)
01.01.2017 – 31.12.2017
FAU Emerging Talents Initiative (ETI) Funding

Staedtler Stiftung WW/eh 13/15 (Germany)
01.06.2015 – 30.05.2017
Wachstum von Silizium-Germanium-Karbid Halbleiterschichten mittels Chemischer Gasphasenabscheidung für Photovoltaikanwendungen

Thermo Fisher Scientific Messtechnik GmbH (Germany)
01.01.2017 – 30.06.2017
Entwicklung von Schichten auf der Basis von ZnS:Ag - Mikrokristallen

14. Teaching

Winter Term 2016/17

Lectures (VORL)

Grundlagen der Halbleiterphysik [GHl], *W. Heiß*

Grundlagen des Kristallwachstums und der Halbleitertechnologie, *P. Wellmann*

Materialien der Elektronik und der Energietechnik [MEET-V], *P. Wellmann*

Materialien und Bauelemente für die Optoelektronik und Energietechnologie: Grundlagen [OpEt-G], *Ch. J. Brabec*

Nano-Bauelemente-Sensoren, MEMS, Micromachining [(NanoDev)], *N.N.*

Nanospektroskopie [NanoSpek], *W. Heiß, M. Batentschuk*

Photophysics and Electronic Transport [PhPhys], *H.-J. Egelhaaf, Ch. J. Brabec*

Technische Grundlagen medizinischer Diagnostikverfahren [TGmD], *M. Thoms*

Werkstoffe und Verfahren der medizinischen Diagnostik I [WVmDI], *M. Thoms*

Werkstoffkunde für Studierende der Elektrotechnik (EEI) [Werkstoffk.(ET)], *P. Wellmann*

Exercises and laboratory courses (PR, PJS, SL, UE)

Lab Work Organic Electronics [OE-Pra-MWT], *T. Ameri*

Lab Work Organic Electronics NT [OE-Pra-NT], *T. Ameri*

Praktikum Materialien der Elektronik und der Energietechnologie (5. Sem.) [PR2-ET], *P. Wellmann*

Praktikum Funktionswerkstoffe in der Energietechnologie [FEt-Pra], *P. Wellmann*

Praktikum Nanotechnologie 2 (Master) [NT2-Pra], *W. Heiß, E. Spiecker*

Praktikum Thermoelektrische Eigenschaften in HL [ThEEHL-Pra], *M. Batentschuk*

Praktikum Transporteigenschaften in HL [TrEHl-Pra], *A. Osvet*

Praktikum Wahlfach Crystal Growth [WCrGr-Pra], *P. Wellmann*

Praktikum Werkstoffe 2 [PW2], *M. Batentschuk*

Projektarbeit - Arbeitsgemeinschaft Kristallisation von SiC und CIS [AGK-Sem1], *P. Wellmann*

Projektarbeit – Arbeitsgemeinschaft Organische Photovoltaik [OPV-AG-Sem], *Ch. J. Brabec*

Übung Nano Devices [(ÜbNanoDev)], *N.N.*

Vorbesprechung VL, Termine u. LS-Praktika im WS, *M. Batentschuk, Ch. J. Brabec*

Seminars (AWA, SEM, TUT)

Anleitung zur wissenschaftlichen Arbeit [AnwA], *T. Ameri*

eTutorial - Materialien der Elektronik und Energietechnik [eTUT-WET], *P. Wellmann*

eTutorial Werkstoffkunde für EEI [eTUT-WW-EEI], *P. Wellmann*

Kern-/ Nebenfachseminar i-MEET (für Studierende im 3. MA-Semester) [KF/NF-iMEET-Sem], *Ch. J. Brabec*

Neuere Fragen zu Werkstoffen der Elektronik und Energietechnologie (Lehrstuhl-Seminar) [iMEET-Sem], *Ch. J. Brabec, P. Wellmann, M. Batentschuk*

Seminar "Organic Electronics" [OE-Sem2], *T. Ameri*

Seminar on Solar Energy [SolSem], *CH. Pflaum, Ch. J. Brabec, J. Hornich*

Seminar über Bachelor- und Masterarbeiten [BMBr-Sem], *Ch. J. Brabec*

Seminar über Bachelor-, Master und Doktorarbeiten – Crystal Growth [BMD-CG-Sem], *P. Wellmann*

Seminar über "Solution Processed Semiconductors" [SoPS-Sem], *W. Heiß*

Summer Term 2017

Lectures (VORL)

Devices [Dev], *T. Ameri, K. Forberich*

Elektrische, magnetische, optische Eigenschaften [EOM-V], *W. Heiß*

Elektronische Bauelemente und Materialfragen (Technologie II) [EBM-II], *P. Wellmann*

Halbleiter großer Bandlücke [HLgB], *P. Wellmann*

Halbleitercharakterisierung [HLCh], *W. Heiß*

Kolloidale Nanokristalle [KNKr], *W. Heiß*

Leuchtstoffe [LS], *M. Batentschuk, A. Winnacker*

Materialien und Bauelemente für die Optoelektronik und Energietechnologie: Anwendung [OpEt-A], *Ch. J. Brabec* , *G. Matt*

Organic Electronics-Devices [OE-Dev], *T. Ameri*

Phosphors [Phph], *M. Batentschuk, A. Winnacker*

Technologie der Züchtung von Halbleiterkristallen und Photovoltaik [ZHLPV], *N.N.*

Thin films: processing, characterization and functionalities [ThFPCF], *Ch. J. Brabec, M. Halik, H.-J. Egelhaaf*

Werkstoffe der Elektronik in der Medizin [WEM-V/Ü], *M. Batentschuk, A. Winnacker*

Werkstoffe und Verfahren der medizinischen Diagnostik II [WVmD II], *M. Thoms*

Exercises and laboratory courses (EX, PJS, PR, UE)

Exkursionen, *P. Wellmann*

Kernfachpraktikum I, Werkstoffe der Elektronik und Energietechnik [WEE-Pra l], *M. Batentschuk*

Kernfachpraktikum II [OE-Pra-NT], Wahlfach Organic Electronics, *M. Batentschuk*

Lab Work Organic Electronics [OE-Pra-MWT], *T. Ameri*

Numerische Modellierung des Kristallwachstums mithilfe des Programmpakets COMSOL Multi-Physics [CGL-Comsol], *P. Wellmann*

Praktikum Eigenschaften von Leuchtstoffen [PREgsLs], *M. Batentschuk*

Praktikum optische Eigenschaften von Halbleitern [OptEHL-Pra], *M. Batentschuk*

Praktikum Wahlfach Crystal Growth [CGr-Pra], *P. Wellmann*

Projektarbeit - Arbeitsgemeinschaft Kristallisation von SiC, CIS und CZTS [AG-Kristallisation], *P. Wellmann*

Projektarbeit - Arbeitsgemeinschaft Lösungsprozessierte Halbleiter [AG HL], *Ch. J. Brabec*

Seminars (SEM, SL)

Anleitung zur wissenschaftlichen Arbeit [AnwA], *H.-J. Egelhaaf*

Anleitung zur wissenschaftlichen Arbeit [AnwA-H], *W. Heiß*

How to start a company [HSC-Sem], *Ch. J. Brabec*

Kernfachseminar, *W. Heiß, Assistenten*

Neuere Fragen zu Werkstoffen der Elektronik und Energietechnologie (Lehrstuhl-Seminar) [iMEET-Sem], *Ch. J. Brabec*, *P. Wellmann, M. Batentschuk*

Seminar über Bachelor- und Masterarbeiten, *Ch. J. Brabec*

Seminar über Bachelor- und Masterarbeiten, *W. Heiß*

Seminar über Bachelor- und Masterarbeiten, *P. Wellmann*

Vorbesprechung zum Masterstudium am i-MEET [iMEET-Vb-Ma], *M. Batentschuk, Ch. J. Brabec*

Winter Term 2017/18

Lectures (VORL)

Grundlagen der Halbleiterphysik [GHl], *W. Heiß*

Grundlagen des Kristallwachstums und der Halbleitertechnologie, *P. Wellmann*

Materialien der Elektronik und der Energietechnik [MEET-V], *P. Wellmann*

Materialien und Bauelemente für die Optoelektronik und Energietechnologie: Grundlagen [OpEt-G], *Ch. J. Brabec*

Nano-Bauelemente-Sensoren, MEMS, Micromachining [(NanoDev)], *Lehrbeauftragte*

Nanospektroskopie [NanoSpek], *W. Heiß, M. Batentschuk*

Photo Physics and Electronic Transport [PhPhys], *H.-J. Egelhaaf, Ch. J. Brabec*

Technische Grundlagen medizinischer Diagnostikverfahren [TGmD], *M. Thoms*

Werkstoffe und Verfahren der medizinischen Diagnostik I [WVmDI], *M. Thoms*

Werkstoffkunde für Studierende der Elektrotechnik (EEI) [Werkstoffk.(ET)], *P. Wellmann*

Exercises and laboratory courses (PR, PJS, SL, UE)

Lab Work Organic Electronics [OE-Pra-MWT], *T. Ameri*

Lab Work Organic Electronics NT [OE-Pra-NT], *T. Ameri*

Praktikum Materialien der Elektronik und der Energietechnologie (5. Sem.) [PR2-ET], *P. Wellmann*

Praktikum Funktionswerkstoffe in der Energietechnologie [FEt-Pra], *P. Wellmann*

Praktikum Nanotechnologie 2 (Master) [NT2-Pra], *W. Heiß, E. Spiecker*

Praktikum Thermoelektrische Eigenschaften in HL [ThEEHL-Pra], *M. Batentschuk*

Praktikum Transporteigenschaften in HL [TrEHl-Pra], *A. Osvet*

Praktikum Wahlfach Crystal Growth [WCrGr-Pra], *P. Wellmann*

Praktikum Werkstoffe 2 [PW 2], *M. Batentschuk*

Projektarbeit - Arbeitsgemeinschaft Kristallisation von SiC und CIS [AGK-Sem1], *P. Wellmann*

Projektarbeit -Arbeitsgemeinschaft Organische Photovoltaik [OPV-AG-Sem], *Ch. J. Brabec*

Übung Nano Devices [(ÜbNanoDev)], *Lehrbeauftragte*

Vorbesprechung VL, Termine u. LS-Praktika im WS, *M. Batentschuk, Ch. J. Brabec*

Seminars (AWA, SEM, TUT)

Anleitung zur wissenschaftlichen Arbeit [AnwA], *T. Ameri*

eTutorial - Materialien der Elektronik und Energietechnik [eTUT-WET], *P. Wellmann*

eTutorial Werkstoffkunde für EEI [eTUT-WW-EEI], *P. Wellmann*

Kern-/ Nebenfachseminar i-MEET (für Studierende im 3. MA-Semester) [KF/NF-iMEET-Sem], *Ch. J. Brabec*

Neuere Fragen zu Werkstoffen der Elektronik und Energietechnologie (Lehrstuhl-Seminar) [iMEET-Sem], *Ch. J. Brabec, M. Batentschuk, K. Forberich*

Seminar "Organic Electronics" [OE-Sem2], *T. Ameri*

Seminar on Solar Energy [SolSem], *Ch. Pflaum, Ch. J. Brabec, J. Hornich*

Seminar über Bachelor- und Masterarbeiten [BMBr-Sem], *Ch. J. Brabec*

Seminar über Bachelor-, Master und Doktorarbeiten – Crystal Growth [BMD-CG-Sem], *P. Wellmann*

Seminar über "Solution Processed Semiconductors" [SoPS-Sem], *W. Heiß*

15. Addresses and Maps

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<u>By train:</u>
Railway station **Erlangen.**
Bus line No. 287 direction **"Sebaldussiedlung"**. Bus stop **"Technische Fakultät".** 50 meters to a layout plan; search for **"Insitut für Werkstoffwissenschaften"**.

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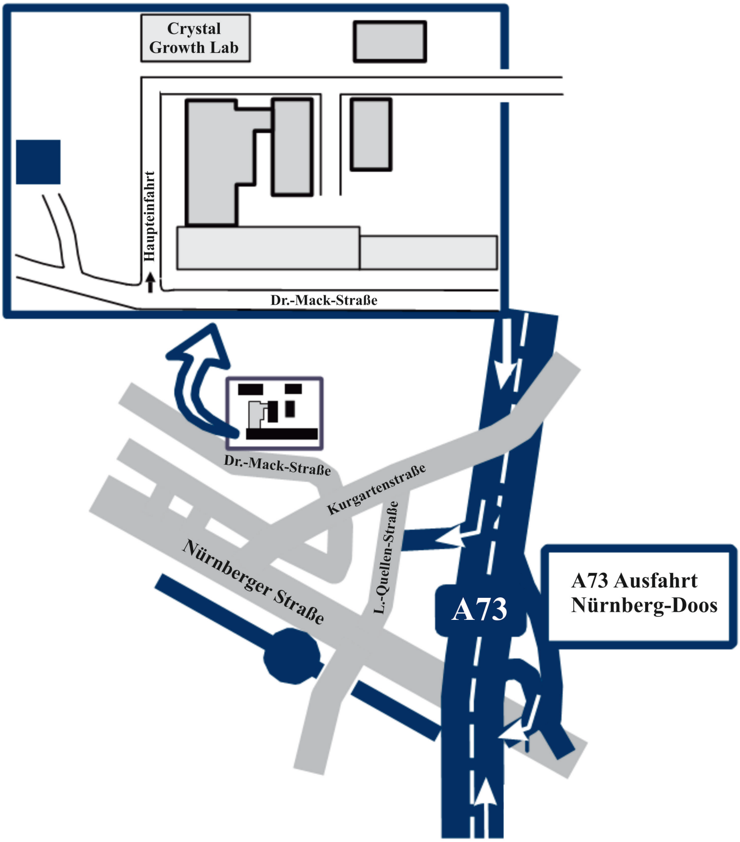

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