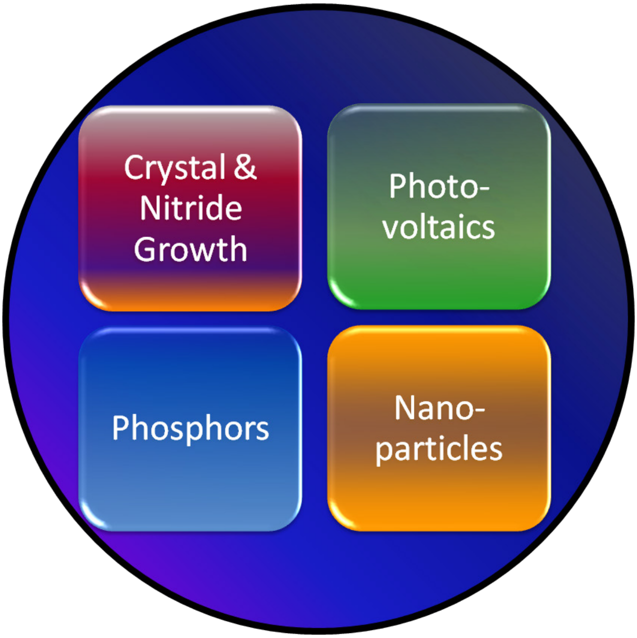
FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG
TECHNISCHE FAKULTÄT

Department of Materials Science and Engineering

i-MEET

Materials for Electronics and Energy Technology



ANNUAL REPORT 2016

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

Die Herausforderung, die deutschen Klimaziele zu erreichen, wird mit jedem Tag größer. Bis 2020 hat sich die Bundesregierung zum Ziel gesetzt, die Emissionen im Vergleich zum Jahr 1990 um 40 Prozent zu reduzieren. Um diesem ambitionierten und zugleich so wichtigen Ziel noch nahe zu kommen, bedarf es in den nächsten Jahren gemeinsame Anstrengungen zwischen Politik, Wirtschaft und angewandter Forschung. Die erneuerbaren Energien müssen zunehmend Systemverantwortung übernehmen können. Da es dafür noch keine Musterlösungen gibt, ist der Forschungsbedarf für neue Konzepte zu Erzeugung, Speicherung und zielgerechten Verteilung von erneuerbarer Energie höher denn je. Am i-MEET, dem EnCN und dem ZAE Bayern sind wir uns dieser Herausforderung und Verantwortung bewusst und werden in 2017 ein breites Themenportfolio beforschen, das verstärkt neue Konzepte für die CO_2 freie Erzeugung und Speicherung von erneuerbarem Strom beforscht und zur Anwendung bringt. Dezentrale Strukturen müssen mehr Verantwortung übernehmen und die Photovoltaik muss als universelle Energiequelle sowohl den Strombedarf von kleinen und flexiblen Anwendungen im Watt Bereich abdecken, aber auch die Leistung von Gigawatt Kraftwerken zur Verfügung stellen können. Ein schneller und flächendeckender Ausbau der Photovoltaik ist daher zwingend notwendig.

i-MEET hat in diesem Jahr Entscheidungen zur weiteren Forschungsstruktur getroffen. Neben der intensiven Forschung an lösungsprozessierten Halbleitern (Heiss), der Halbleiterkristallzucht (Wellmann) und den Halbleiterbauelementen (Brabec) wurde der Aufbau der hochautomatisierten, kombinatorischen Hochdurchsatzforschung von Energiematerialien begonnen. Tobias Stubhan entwickelt im Rahmen eines DFG Antrags eine roboterbasierte Anlage zur kombinatorischen Herstellung von Solarzellen und Andreas Vetter hat die extrem beschleunigte Alterung mit bis zu 700 Sonnen in Betrieb genommen. Die kombinierte Hochdurchsatzforschung mit Robotern und quantenchemischen Big Data Methoden wird richtungsweisend für Entwicklung von Energiematerialien sein, da es keine Alternative gibt um die zum Teil Millionen von möglichen Strukturen zuverlässig und aussagekräftig zu beurteilen. Diese beiden Methoden sollen sicherstellen, dass i-MEET auch in den nächsten Jahren eine internationale Spitzenstellung in der Forschung im Bereich der Halbleiter und Energiematerialien einnimmt.

Wir blicken mit Spannung auf die nächsten Jahre. Die heutigen Forschungsfelder, allen voran die Perovksite, geben uns enorme Möglichkeiten zur nachhaltigen Entwicklung einer gedruckten Elektronik, die alle Aspekte der Hochleistungshalbleiter abdecken. Dabei stehen wir vermutlich erst am Anfang der Entwicklungen, nicht am Ende.

An dieser Stelle möchte ich unseren Studenten, Doktoranden, Mitarbeitern und Gruppenleitern zu den großartigen Leistungen in 2016 gratulieren und mich bei Ihnen für Ihr Engagement und Ihren großen Einsatz bedanken. 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 Kooperationspartner und Unterstützern des i-MEET danke ich für die erfolgreiche Zusammenarbeit in 2016 und wünsche viel Spaß beim Lesen unseres Tätigkeitsberichts.

Christoph Brabec

Preface

Germany´s challenge to meet the climate goals for 2020 and 2050 is growing continuously. The original 2020 target of the German federal government is to reduce CO_2 emissions by 40 % compared to 1990.

Meeting this goal will require national joined efforts between politics, economy, society and applied research. Renewable energies need to take over more responsibility for the whole energy system. As we do not have blue-prints or a strategic energy roadmap how to meet these goals, the need for novel scientific and technological concepts to produce, store and distribute renewable energy is higher than ever before.

i-MEET together with the partners at EnCN and the ZAE Bayern are aware of this challenge and will contribute to it in multiple aspects and directions. The decentralized and centralized generation of photovoltaic electricity needs to take even more responsibility for the Bavarian and German energy system, as photovoltaics is the still the only power source being capable of covering all applications from the milliwatt regime to the gigawatt regime at competitive costs. Photovoltaics has become the cheapest technology for new power plants in Bavaria in 2016 and the fast and nationwide rollout of photovoltaics is eminent.

i-MEET has set its future research directions. On one hand we will intensify research on solution processed semiconductors (AG Heiss), on semiconductor crystal growth (AG Wellmann) and on semiconductor devices (AG Brabec). On the other hand we started the build-up of a new research direction: the highly automated, combinatorial high throughput investigation and development of energy materials. Tobias Stubhan started with the development of a robot-based research tool for the combinatorial processing of energy devices, clearly with the first focus on organic and perovskite solar cells. Andreas Vetter finished building several extremely accelerated lifetime testing units allowing to stress materials and devices with up to 700 suns while keeping the temperature under precise control. Combinatorial high throughput research with robots and quantum chemical big data methods is trend-setting for the development of the next generation of energy materials. These two methods shall guarantee i-MEET´s international top position in the R&D of semiconductors and energy materials.

We are looking forward with excitement into the future. Today´s research directions - first and foremost research on perovskites - bear an enormous potential for the sustainable development of a printed electronics future, covering all aspects including high performance semiconductors. We are facing exciting next years.

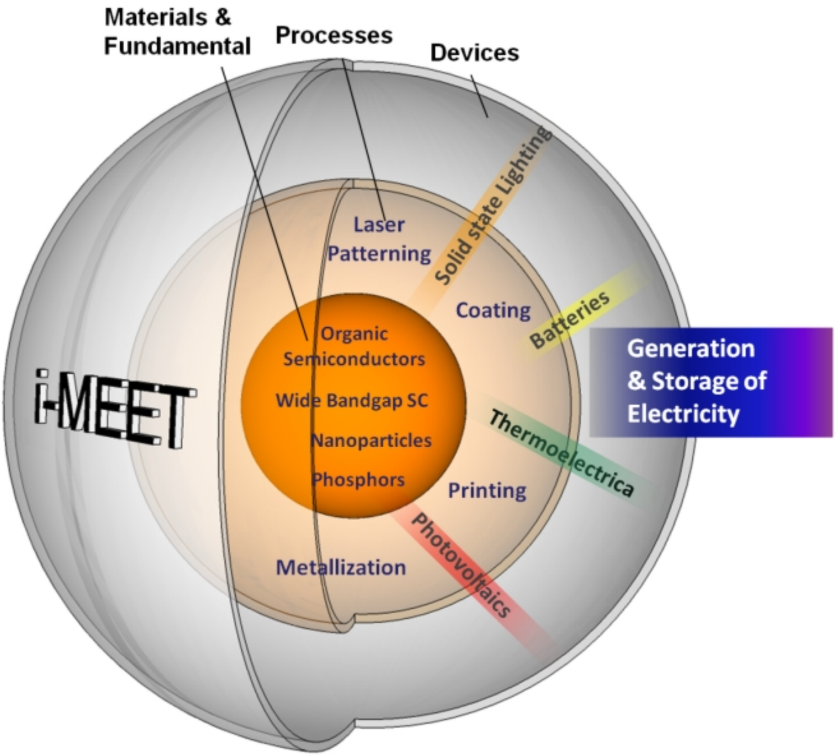
At this stage I want to express my gratitude to our students, PhD students, postdocs and group leaders to their fantastic scientific achievements in 2016. We published over 60 manuscripts, 8 of them in the Nature family and in Energy & Environmental Science. Specific and particular thanks to our technical 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 the successful cooperation in 2016! 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)

(Miroslaw Batentschuk)

Erlangen, July 2017

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.
Hans-Joachim Egelhaaf


Dr.-Ing.
Jochen Friedrich


Dr. rer. nat
Elke Meißner

Technical staff


Elena Epelbaum


Tina Foth

Winfried Habel


Silvan Heilscher


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.

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i-MEET

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Doctoral candidate
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(Hons)
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Lili Ke
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Stefan Langner
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Dr.
Ning Li
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Reza Mokhtari
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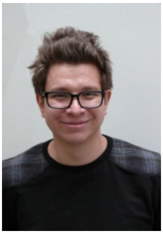

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MSc
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Dr.
Michael Salvador
Postdoc
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George Spyropoulos
MSc
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Dr. Tobias Stubhan
Postdoc
Doctoral candidate
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Chen Xie
MSc
Doctoral candidate
i-MEET

Chaohong Zhang
MSc
Doctoral candidate
ZAE

Dipl.-Ing.
Hong Zhang
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 for the detection of photo-currents in steady-state as well as time-resolved (ns regime) overing a wide spectral regime from the UV-VIS to the Mid-IR have been developed.

Thomas Heumüller
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Simon Kahmann
MSc
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Moses Richter
MSc (Hons)
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
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Shuai Gao
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Doctoral candidate
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Julian Hornich
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Dipl.-Ing.
Johannes Krantz
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Kerstin Krebs
MSc
Doctoral candidate
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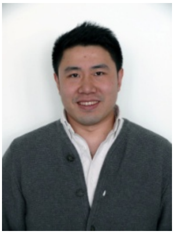

Yilei Shen
MSc
Doctoral candidate
i-MEET

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, dyes 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
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Lili Ke
MSc
Doctoral candidate
i-MEET

Rezvan Soltani
MSc
Doctoral candidate
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Imaging and Thermosensorics (IMT)

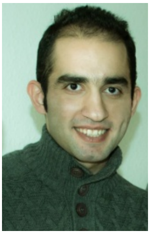
(Scientifical staff, doctoral candidates)

Dr. Andreas Vetter
Group leader

The group “Imaging & Thermosensorics” is dedicated to developing imaging methods and exploring accelerated life time testing of materials, in particular at high temperature. One important task of the group is to develop and apply innovative test and measurement methods. The group has a strong experience in precise infrared imaging methods. Also, different imaging methods have been extensively applied to characterize PV-cells and PV-modules.

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

Johannes Hepp
MSc
Doctoral candidate
ZAE



Amir Hashemi
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Dr.
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Postdoc
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MSc
Andre Karl
Doctoral candidate
i-MEET

B. Eng.
Sergej Lohvitki
Technician
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
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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
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Dipl.-Ing.
Lars Fahlbusch
Doctoral candidate
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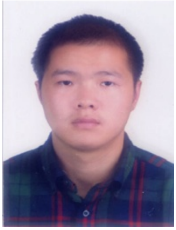

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Ayat Hassanien
MSc
Doctoral candidate
i-MEET

Hossein Khodamoradi
MSc
Doctoral candidate
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Dr. Dipl.-Ing
Ulrike Künecke
Scientifical staff
i-MEET

Dipl.-Ing.
Georg Neubauer
Doctoral candidate
i-MEET

Saskia Schimmel
MSc
Doctoral candidate
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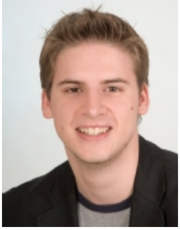


Philipp Schuh
MSc
Doctoral candidate
i-MEET

Matthias Schuster
MSc
Doctoral candidate
i-MEET

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

Dipl.-Ing.
André Zweschke
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.

Iftikhar Channa
MEng

Bernd Doll
MSc

Dipl.-Phys.
Frank Fecher

Johannes Hepp
MSc

Dipl.-Phys.
Ulrich Hoyer

Luca Lucera
MSc

Philipp Maisch
MSc

Atif Makhdoom
MEng

Anastasiia Solodovnyk
MSc

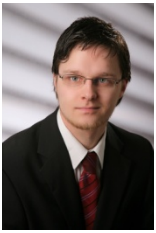
G. Spyropoulos
MSc

Dipl.-Phys.
Arne Riecke

Dipl.-Ing.
Stephan Wittmann

External doctoral candidates


Armin Heinrichsdobler
MSc
Osram


Meng
Tobias Kötter
Siemens


Dipl.-Pys.
Daniel Riedel
Osram


Dipl.-Ing.
Tobias Sauermann
Belectric

Dipl.-Ing
Philipp Schwamb
Osram

Visitors

04.05.2015-23.03.2016
Rezvan Soltani, MSc (Amirkabir University of Technology, Tehran, Iran)
Hybrid polymer solar cell based on PbS quantum dots/carbon nanotube nanoarchitectures

25.09.2016-01.10.2016
Prof. Dr. hab. Yuriy Zorenko (Institute of Physics Kazimierz Wielki Univerity Bydgoszcz, Poland)
Phosphors of doped Silicat Garnets for high power white light emitting diodes

3. Bachelor Theses

Baderschneider, Kevin (Brabec)
Einfluss von Beschichtungsmethoden und Tintenformulierung auf die optischen und elektrischen Eigenschaften von Silber Nanodraht Schichten

Barten, Florian (Wellmann)
Spektroskopische Untersuchung von Zwischenbandübergängen in co-dotierten 3C-SiC-Schichten

Dobsch, Marko (Wellmann)
Untersuchung der Kristallisation von GaN unter ammonosauren Bedingungen mit dem Mineralisator NH_4F

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

Eigen, Andreas (Wellmann)
Entwicklung einer nasschemisch abgeschiedenen ZnS-Pufferschicht für die Anwendung in $CuInSe_2$*-Solarzellen*

Fischer, Julian (Wellmann)
Untersuchung der Zusammensetzung von Si-Ge-C Niedertemperatur CVD-Schichten

Graf, Lorenz (Wellmann)
Prozessoptimierung bei der nasschemischen Herstellung eines dichten $CuInSe_2$*-Solarzellenabsorbers auf Basis von Cu-In und Se Nanopartikel-Schichtstapeln*

Höning, Kilian (Wellmann)
Bestimmung der GaN Löslichkeit unter ammonothermalen Bedingungen durch differentielle Auswertung der Heizrate

Körfer, Julien (Wellmann)
Entwicklung eines experimentellen Strömungsmodells der ammonothermalen Kristallisation

Knüttel, Judith (Wellmann)
Spektroskopische Charakterisierung der Defektdichte von 3C-SiC Volumenkristallen

Lederer, Maximilian (Wellmann)
Optimierung des Wachstums von großflächigem, epitaktischen Graphen auf SiC durch Homogenisierung der Si-Sublimationsbedingungen

Leimbach, Steffen (Heiss)
Nanocrystals for light up-conversion
Hocheffiziente Kern-Schale Nanokristalle für die Licht Aufkonversion

Nguyen, Tien Lin (Wellmann)
Untersuchung der Schichtbildung eines dichten $CuIn(SxSe_{1-x})_2$ *Solarzellenabsorbers über eine Austauschreaktion von* $CuInS_2$ *Nanopartikeln mit Se*

Ottinger, Bettina (Wellmann)
Ammonothermale Kristallisation von GaN im Ag-Liner mithilfe des Mineralisators NH_4F

Sisterhenn, Philipp (Wellmann)
Herstellung und Charakterisierung eines dichten $CuInSe_2$*-Solarzellenabsorbers aus Cu-In und Se Nanopartikel-Schichtstapeln*

Stapf, Dominik (Wellmann)
Untersuchung der Grenzfläche zwischen Mo und nanopartikulären $CuInSe_2$*-Absorberschichten für die Anwendung in Solarzellen*

Voll, Johannes C. (Brabec)
Effizienzsteigerung in organischen Solarzellen durch kontrollierte UV-Behandlung

Weghorn, Steffen (Brabec)
Prozessentwicklung zur Herstellung organischer Solarzellen für das EAM-Lab

4. Master Theses

Ackermann, Alexander (Wellmann)
Entwicklung einer diffusionshemmenden SiC-Tiegelbeschichtung für den Einsatz bei der gerichteten Erstarrung von PV-Silizium

Arzig, Matthias (Wellmann)
Optimierung der Prozessparameter bei der Herstellung von epitaktischem Graphen auf Siliziumkarbid unter Argon-Atmosphäre

Doll, Bernd (Brabec)
Investigation of the film formation of doctor bladed pervoskite layers for solar cell application as a function of humidity

Kazerouni, Negar (Brabec)
High efficient organic ternary solar cells, case study on open circuit voltage (Voc)

Paulke, Ingo (Diploma thesis, Brabec)
Spektraloptische Messungen an CIGS-Solarzellen zur Inline-Qualitätskontrolle

Reuther, Jonas (Brabec)
Electrical characterization of organic solar cells at low temperatures

Gast, Jessica (Brabec)
Development of phosphor layers for contactless measurement of temperature via thermal imaging

Bergmann, Johannes (Brabec)
Processing of hybrid organic-inorganic perovskite ink: from powder to device Application

Pallach, Sandra (Brabec)
Degradation of organic photodiodes under x-ray irradiation

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

Bronnbauer, Carina (Brabec, i-MEET)
Printed dielectric mirrors for organic solar cells

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

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

Chen Haiwei (Brabec, i-MEET)
Hihgh-Performance and stable 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

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

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

Fecher, Frank (Brabec, ZAE)
Electrical simulations of thin film photovoltaic modules

Gao, Shuai (Brabec, i-MEET)
Dielectric mirrors and their applications

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

Gasparini, Nicola (Brabec, i-MEET)
Controlling charge carrier recombination in ternary organic solar cells

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

Güldal, Nusret Sena (Brabec, i-MEET)
Investigation of drying kinetics of hybrid/organic solar cells

Guo, Fei (Heiss, i-MEET)
Material and Process Engineering of Printed Semitransparent Organic Solar Cells and Advanced Multi-junction Architectures

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)
PV fibers

Heinrichsdobler Armin (Brabec extern, OSRAM OLED GmbH.)
Druckprozesse für OLED-Substrate

Hepp, Johannes (Brabec, ZAE)
Improving of Imaging Techniques for Quality Control of Thin Film Solar Cells

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

Hou, Yi (Brabec, i-MEET)
Multicomponet chalcopyrite and kesterite inorganic nanocrystals for solar cell applications

Hoyer, Ulrich (Brabec, ZAE)
Analyse von organischen Photovoltaik-Zellen mittels bildgebender Elektrolumineszenzmessung

Kahmann, Simon (Brabec, i-MEET)
Hybrid photovoltaics based on organic polymers / semiconductor nanoparticle composites

Ke, Lili (Brabec, i-MEET)
A Series of Novel Silicon Phthalocyanines / Naphthalocyanine as Near Infrared Sensitizers in Organic Ternary and Quaternary Solar Cells

Khanzada, Laraib (Brabec, i-MEET)
The development and characterization of low cost, abundant, non-toxic and low temperature solution processable inorganic semiconductors for photovoltaic applications

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

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

Kötter, Tobias (Brabec, external)
Hochleistungsdichte Phasenwechsel-Komposit-Materialien für das Thermomanagement von elektrotechnischen Systemen

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

Levchuk, Ievgen (Brabec, i-MEET)
Synthesis and optimization of semiconductor colloidal nanocrystals for solar cell application

Liu, Chao (Brabec, i-MEET)
Designing Novel n-Type Water/Alcohol Soluble Conjugated Electrolytes for Organic and Hybrid Photovoltaic Application

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

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

Perea Ospina, Jose Dario (Brabec, i-MEET)
Solubility investigation based on COSMO-RS approach

Ramirez Quiroz, César Omar (Brabec, i-MEET)
Hybrid tandem solar cells based on PbI perovskite

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

Riecke, Arne (Brabec, ZAE)
Rekristallisation dünner Siliziumschichten auf Fremdsubstraten für photovoltaische Anwendungen und Anpassung der Zonenschmelzanlage (ZMR)

Sauermann, Tobias (Brabec, external)
Degradation Mechanisms in Organic Solar Cells

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

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

Schwamb, Philipp (Brabec, external)
Flexible white OLEDs

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

Shrestha, Shreetu (Brabec, i-MEET)
Direct X-ray detectors based on PbI perovskite

Spyropoulos, George (Brabec, ZAE)
Design and fabrication of novel and printable multi-junction organic solar cells

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

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

Zhang, Chaohong (Brabec, i-MEET)
Synthesis & characterization of novel Fullerene-grafted compounds

Zhang, Hong (Brabec, i-MEET)
Design of Interfacial Layers for Organic Solar Cells

Zweschke, André (Wellmann, i-MEET)
Numerische Modellierung der Phasenbildung von CIS Solarzellenasorberschichten

Doctoral Theses Completed

15.03.2016
Heumüller Thomas (Brabec, i-MEET)
Impact of Microstructure on the Photostability of Organic Bulk Heterojunction Solar Cells

01.04.2016
Krantz, Johannes (Brabec)
Transparent and Opaque Electrode Materials Processed from Solution for Application in Thin Film Organic Electronics

17.06.2016
Riedel, Daniel (Brabec, external)
Internal light extraction in organic light emitting devices
Polymere Streuschichten zur Lichtauskopplung aus organischen Leuchtdioden

07.09.2016
Solodovnyk, Anastasiia (Brabec, ZAE)
Design and In-Depth Optical Studies of Advanced Material Concepts for Luminescent Down-Shifting Coatings for Photovoltaics

04.11.2016
Lucera Luca (Brabec, ZAE)
Closing the Efficiency Gap Between Lab-produced Organic Solar Cells and Roll-to-Roll Printed Solar Modules

06.12.2016
Bachmann, Jonas (Brabec)
Organic Plastic Solar Modules Characterized by Thermal Methods

6. Awards

Maisch, Philipp

Best Paper Award 12th IEEE MID conference
Fantastic Job by Philipp and the Solar Factory's Inkjet Team! Their work on "Inkjet printing of highly conductive nanoparticle dispersions for organic electronics" won the best paper award at the IEEEs 12th MID conference.

Bronnbauer, Carina
Winner SAOT Videocompetition 2016
SAOT einen Aufenthalt über ca. 3,5 Monate an der University of Queensland, Brisbane

Ameri, Tayebeh
Christiane Nüsslein-Volhard foundation, Germany

7. Publications (Full Papers and Conference Proceedings)

Full Papers

Baran, D., Kirchartz, T., Wheeler, S., Dimitrov, S., Abdelsamie, M., Gorman, J., Ashraf, R.S., Holliday, S., Wadsworth, A., Gasparini, N., Kaienburg, P., Yan, H., Amassian, A., Brabec, C.J., Durrant, J.R., McCulloch, I.
Reduced voltage losses yield 10% efficient fullerene free organic solar cells with >1 V open circuit voltages
*Energy and Environmental Science, **9 (12)**, pp. 3783-3793, 2016*
DOI: 10.1039/c6ee02598f

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, pages 8, Article in press, 2016
DOI: 10.1038/nmat4797

Bronnbauer, C., Gasparini, N., Brabec, C.J., Forberich, K.
Guideline for Efficiency Enhancement in Semi-Transparent Thin-Film Organic Photovoltaics with Dielectric Mirrors
*Advanced Optical Materials, **4 (7)**, pp. 1098-1105, 2016*
DOI: 10.1002/adom.201600080

Bronnbauer, C., Osvet, A., Brabec, C.J., Forberich, K.
Semitransparent Organic Light Emitting Diodes with Bidirectionally Controlled Emission
*ACS Photonics, **3 (7)**, pp. 1233-1239, 2016*
DOI: 10.1021/acsphotonics.6b00234

Chen, H., Hou, Y., Halbig, C.E., Chen, S., Zhang, H., Li, N., Guo, F., Tang, X., Gasparini, N., Levchuk, I., Kahmann, S., Ramirez Quiroz, C.O., Osvet, A., Eigler, S., Brabec, C.J.
Extending the environmental lifetime of unpackaged perovskite solar cells through interfacial design
*Journal of Materials Chemistry A **4 (30),** pp. 11604-11610, 2016*
DOI: 10.1039/c6ta03755k

Chen, S., Hou, Y., Chen, H., Richter, M., Guo, F., Kahmann, S., Tang, X., Stubhan, T., Zhang, H., Li, N., Gasparini, N., Quiroz, C.O.R., Khanzada, L.S., Matt, G.J., Osvet, A., Brabec, C.J.
Exploring the Limiting Open-Circuit Voltage and the Voltage Loss Mechanism in Planar $CH_3NH_3PbBr_3$ Perovskite Solar Cells(2016)
*Advanced Energy Materials, **6 (18)**, art. no. 1600132, 2016*
DOI: 10.1002/aenm.201600132

Chepyga, L.M., Jovicic, G., Vetter, A., Osvet, A., Brabec, C.J., Batentschuk, M.
Photoluminescence properties of thermographic phosphors YAG:Dy and YAG:Dy, Er doped with boron and nitrogen
*Applied Physics B: Lasers and Optics, **122 (8)**, art. no. 212, 2016*
DOI: 10.1007/s00340-016-6487-8

Christos L. Chochos, Ranbir Singh, Min Kim, Nicola Gasparini, Athanasios Katsouras, Chandramouli Kulshreshtha, Vasilis G. Gregoriou, Panagiotis E. Keivanidis, Tayebeh Ameri, Christoph J. Brabec, Kilwon Cho, and Apostolos Avgeropoulos
Enhancement of the Power Conversion Efficiency in Organic Photovoltaics by Unveiling the Appropriate Polymer Backbone Enlargement Approach
Advanced Functional Materials, pages 9, Article in press, 2016
DOI: 10.1002/adfm.201504953

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, pages 10, Article in press, 2016
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Overcoming Interfacial Losses in Solution-Processed Organic Multi-Junction Solar Cells
Advanced Energy Materials, pages 10, Article in press, 2016
DOI: 10.1002/aenm.201601959

Sule Erten-Ela, Haiwei Chen, Andreas Kratzer, Andreas Hirsch and Christoph J. Brabec
Perovskite solar cells fabricated using dicarboxylic fullerene derivatives
*New Journal of Chemistry **40**, pp. 2829-2834, 2016*
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Nicola Gasparini, Xuechen Jiao, Thomas Heumueller, Derya Baran, Gebhard J. Matt, Stefanie Fladischer, Erdmann Spiecke, Harald Ade, Christoph J. Brabec and Tayebeh Ameri
Designing ternary blend bulk heterojunction solar cells with reduced carrier recombination and a fill factor of 77%
*Nature Energy **16118**, pages 10, 2016*
DOI: 10.1038/NENERGY.2016.118

Güldal, N.S., Berlinghof, M., Kassar, T., Du, X., Jiao, X., Meyer, M., Ameri, T., Osvet, A., Li, N., Destri, G.L., Fink, R.H., Ade, H., Unruh, T., Brabec, C.J.
Controlling additive behavior to reveal an alternative morphology formation mechanism in polymer: Fullerene bulk-heterojunctions
*Journal of Materials Chemistry A, **4 (41)**, pp. 16136-16147, 2016*
DOI: 10.1039/c6ta07023j

Nusret S. Güldal, Thaer Kassar, Marvin Berlinghof, Tayebeh Ameri, Andres Osvet, Roberto Pacios, Giovanni Li Destri, Tobias Unruh and Christoph J. Brabec
Real-time evaluation of thin film drying kinetics using an advanced, multi-probe optical setup
Journal of Materials Chemistry C, pages 9, Article in press, 2016
DOI: 10.1039/c5tc03448e

Heiss, W., Brabec, C.
X-ray imaging: Perovskites target X-ray detection
Nature Photonics ***10 (5),*** *pp. 288-289, 2016*
DOI: 10.1038/nphoton.2016.54

Johannes Hepp, Florian Machui, Hans-J. Egelhaaf, Christoph J. Brabec & Andreas Vetter
Automatized analysis of IR-images of photovoltaic modules and its use for quality control of solar cells
Energy Science & Engineering ***4 (6)****, pp. 363-371, 2016*
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Morphological and electrical control of fullerene dimerization determines organic photovoltaic stability
Energy & Environmental Science **9**, *pp. 247-256, 2016*
DOI: 10.1039/c5ee02912k

Holliday, S., Ashraf, R.S., Wadsworth, A., Baran, D., Yousaf, S.A., Nielsen, C.B., Tan, C.-H., Dimitrov, S.D., Shang, Z., Gasparini, N., Alamoudi, M., Laquai, F., Brabec, C.J., Salleo, A., Durrant, J.R., McCulloch, I.
High-efficiency and air-stable P3HT-based polymer solar cells with a new non-fullerene acceptor
Nature Communications 7, art. no. 11585, pages 11, 2016
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Overcoming the Interface Losses in Planar Heterojunction Perovskite-Based Solar Cells
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Advanced Functional Materials ***26****, pp. 5248-5254, 2016*
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A Series of Pyrene-Substituted Silicon Phthalocyanines as Near-IR Sensitizers in Organic Ternary Solar Cells
Advanced Energy Materials, pages 13, Article in press, 2016
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Khanzada, L.S., Levchuk, I., Hou, Y., Azimi, H., Osvet, A., Ahmad, R., Brandl, M., Herre, P., Distaso, M., Hock, R., Peukert, W., Batentschuk, M., Brabec, C.J.
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The Journal of Physical Chemistry C ***120****, pp. 19848-19855, 2016*
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Industrially scalable and cost-effective Mn^{2+} doped $Zn_xCd_{1-x}S/ZnS$ nanocrystals with 70% photoluminescence quantum yield, as efficient down-shifting materials in photovoltaics
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Deciphering the Role of Impurities in Methylammonium Iodide and Their Impact on the Performance of Perovskite Solar Cells
Advanced Materials Interfaces ***3 (22)****, art. no. 1600593, pages 10, 2016*
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Highly efficient, large area, roll coated flexible and rigid OPV modules with geometric fill factors up to 98.5% processed with commercially available materials
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Effects of electron-with drawing group and electron-donating core combinations on physical properties and photovoltaic performance in D-π-A star-shaped small molecules
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Journal of Materials Chemistry C ***4 (29)****, pp. 7061-7076, 2016*
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Inkjet printed silver nanowire percolation networks as electrodes for highly efficient semitransparent organic solar cells
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Time-Dependent Morphology Evolution of Solution-Processed Small Molecule Solar Cells during Solvent Vapor Annealing
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Fully Solution-Processed Small Molecule Semitransparent Solar Cells: Optimization of Transparent Cathode Architecture and Four Absorbing Layers
Advanced Functional Materials, pages 8, Article in press, 2016
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*Advanced Energy Materials **6 (14)**, art. no. 1600515, pages 9, 2016*
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*Journal of Materials Chemistry A **4 (37)**, pp. 14234-14240, 2016*
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Giant Rashba Splitting in CH3NH3PbBr3 Organic-Inorganic Perovskite
*Physical Review Letters **117 (12)**, art. no. 126401, pages 6, 2016*
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Reduced voltage losses yield 10% efficient fullerene free organic solar cells with >1 V open circuit voltages†

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Optimization of the energy levels at the donor–acceptor interface of organic solar cells has driven their efficiencies to above 10%. However, further improvements towards efficiencies comparable with inorganic solar cells remain challenging because of high recombination losses, which empirically limit the open-circuit voltage (V_{oc}) to typically less than 1 V. Here we show that this empirical limit can be overcome using non-fullerene acceptors blended with the low band gap polymer PffBT4T-2DT leading to efficiencies approaching 10% (9.95%). We achieve V_{oc} up to 1.12 V, which corresponds to a loss of only $E_g/q - V_{oc} = 0.5 \pm 0.01$ V between the optical bandgap E_g of the polymer and V_{oc}. This high V_{oc} is shown to be associated with the achievement of remarkably low non-geminate and non-radiative recombination losses in these devices. Suppression of non-radiative recombination implies high external electroluminescence quantum efficiencies which are orders of magnitude higher than those of equivalent devices employing fullerene acceptors. Using the balance between reduced recombination losses and good photocurrent generation efficiencies achieved experimentally as a baseline for simulations of the efficiency potential of organic solar cells, we estimate that efficiencies of up to 20% are achievable if band gaps and fill factors are further optimized.

Broader context

Recently, organic solar cells have reached power conversion efficiencies (PCE) up to 12%. However, the compromise between voltage loss and external quantum efficiency (EQE) still limits the PCE of these devices for further improvements with devices providing open circuit voltages (V_{oc}) > 1 V. In this report, we present a guideline for reducing the compromise between voltage loss and EQE by using small-molecule acceptors and achieve PCEs up to 10% without the need for fullerene acceptors. By replacing fullerenes with different small molecule acceptors, we were able to achieve efficiencies up to 10% with V_{oc} values >1 V (up to 1.12 V) and EQE values approaching 76%. These improvements are achieved by suppressing recombination losses in the donor:acceptor blends and optimizing the nano-structure for efficient charge separation at the interface. Our simulations predict that these suppressed losses with high EQE values can yield up to 20% organic solar cells provided further optimization of fill factor and band gap is possible in the future.

One of the main criteria for highly efficient solar cells is the combination of high photocurrent densities (J_{sc}) with high open-circuit voltages (V_{oc}). In the case of organic solar cells, the heterojunction between an electron donating and an electron accepting material is required for efficient exciton dissociation leading to a compromise between these two parameters. In order to achieve the highest possible photocurrent some of the achievable V_{oc} has to be sacrificed.[1–3] Thus, a substantial amount of work on organic photovoltaics has focused on minimizing the voltage loss required for exciton dissociation and to achieve the best possible compromise between photocurrent and photovoltage.[4–9] Fig. 1 demonstrates the empirical consequences of this compromise showing that the smaller the

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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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Guideline for Efficiency Enhancement in Semi-Transparent Thin-Film Organic Photovoltaics with Dielectric Mirrors

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Semi-transparent organic solar cells (ST-OSCs) show a unique potential to be integrated in windows due to their outstanding characteristics such as high transparency and color-adjustability. In order to achieve both, high transparency and high efficiency, the use of dielectric mirrors is an excellent concept. However, such a mirror will not only improve the photocurrent generated by a solar cell but also cause losses in transparency. In this work, a theoretical model is developed that predicts the effect of the dielectric mirror on the balance between photocurrent enhancement and transparency loss depending on the spectral shape of the ST-OSC absorption. Experimental investigations with three fully printed ST-OSCs showing different absorption characteristics underline the validity of these studies. It is concluded that ST-OSCs with broad absorption spectra ranging from the short wavelength region over the visible to at least 950 nm are most suitable for the implementation of a dielectric mirror. A narrower absorption spectrum or a shift of the spectrum toward longer wavelengths makes an increase in photoactive layer thickness more beneficial than the attachment of a dielectric mirror. Moreover, the dielectric mirror approach is an excellent strategy to obtain high photocurrents for materials which cannot be processed at high active layer thicknesses.

1. Introduction

The ideal thin-film semi-transparent organic solar cell (ST-OSC) combines high transparency in the visible region with high power conversion efficiency (PCE). For achieving high PCEs, factors such as (sheet-, shunt-, and serial-) resistances, nanomorphology, selective charge collection of the interfacial layers, offset energy levels of the donor and acceptor, and their molar ratio have to be taken into account.[1–7] High device transparencies are realized by using electrodes, buffer layers, and photoactive materials with low absorption in the human eye sensitivity region (≈400–700 nm). To still guarantee high photon harvesting, low band gap materials are used preferentially as they provide strong photosensitivity up to the near-infrared region.[8,9] However, none of these photoactive materials are fully transparent in the visible region. The transparency is therefore mainly determined by the photoactive layer thickness. According to the Beer–Lambert law, the thicker the layer, the stronger the light absorption and the less transparent the device. Since the number of generated charge carriers is also determined by the absorption, the layer thickness affects the balance between photocurrent and transparency. Mentionable, for reflective structures (like SC with a highly reflective electrode) the absorption is not directly proportional to the thickness but features maxima and minima due to interference effects. However, in ST-SC those maxima and minima are collapsed into shoulders (Figure S1, Supporting Information). Nevertheless, an increase in the photoactive layer thickness does not generally lead to an increased PCE due to the limited mobility and lifetime of the charge carriers.[10–12]

We previously reported in a theoretical study that differently colored bulk heterojunction ST-OSC with 30% transparency can reach maximum up to 12% PCE.[13] To overcome this limitation, different light management strategies like up- or downconversion layers, patterned substrates, microcavities, plasmonic metal nanostructures, anti-reflection coatings, or dielectric mirrors have been reported in the literature.[14–20] The use of dielectric mirrors (also known as Bragg mirrors, 1D photonic crystals, or dichroic filters) which are based on thin-film interference is an especially outstanding method. In this approach, photons which are not absorbed while passing through the ST-OSC are wavelength selectively reflected at the back of the device via the dielectric mirror and pass through the device again. The position, the value, and the spectral width of the reflection maximum can be adjusted to any desired value. As a result, a dielectric mirror can increase the light-harvesting efficiency of an ST-OSC while preserving high transparency, or change the device color in a desired way.[20–22] Moreover, due to recent progress in fabrication methods the dielectric mirrors can now be fully printed, making this approach also

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Semitransparent Organic Light Emitting Diodes with Bidirectionally Controlled Emission

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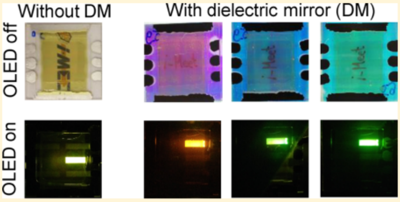
Supporting Information

ABSTRACT: Semitransparent OLEDs are a candidate for large-area eco-friendly light sources that can be integrated into building facades, suggesting colorful windows that become luminescent if the OLED is switched on. However, since the light is emitted in two directions, smart light engineering has to be implemented to direct the light into a preferred direction and to prevent for instance huge energetic losses to the outside of a building. We introduce an unprecedented device architecture, composed of a dielectric mirror attached to a semitransparent OLED. Such a system features a dual functionality that depends on the viewing direction: changing the color perception and/or enhancing the light directionality while still preserving a high overall device transparency. First, we motivate the potential of this concept with a theoretical study, showing that broad modifications in the color range can be realized via device optimization and that the maximum possible emission enhancement of the OLED is limited only by the transparency of the interfacial layers and the electrodes. Then, experimental investigations with a semitransparent yellow OLED (transparency = 58.2%) in combination with six different dielectric mirrors validate the theoretical results. Retaining the same color perception, up to 80% of the total emitted light can be directed toward one side while the color is modified at the other side of the device stack. Here, modifications from yellow to purple to dark or light blue can be realized.



KEYWORDS: *color modification, dielectric mirror, fully printed, light management, OLED, semitransparent*

Organic light emitting diodes (OLEDs) show a huge potential to be the next-generation light source, as they are thinner, more eco-friendly with respect to energy consumption and materials, easier to fabricate due to solution processability, not restricted to any shape, and more flexible or even stretchable and provide wider viewing angles than the present lighting systems.[1−6] Furthermore, and in contrast to their inorganic counterpart, OLEDs enable the production of large-area flat panel lighting systems without any light distribution elements.[7,8] In principle, an OLED consists of an organic electroluminescent material sandwiched between two electrodes. Additional electron- and hole-transporting layers at the anode and cathode interfaces can further improve charge carrier injection and thus enhance the overall device performance. Apparently, the interfacial layers as well as at least one electrode have to be semitransparent to guarantee light extraction. OLEDs with two semitransparent electrodes allow the realization of window integrated light modules or transparent displays and have already been reported.[6,9−11] While the emitted color spectrum of OLEDs is mainly a function of the band gap of the emitter materials, their brightness depends on the applied voltage and the light extraction efficiency. The bandwidth of most emitter materials is relatively narrow and does not extend over the whole visible region. However, there are two main approaches for OLEDs that help to generate broad emission spectra, including white light.[12] One technique is based on the doping of a single organic electroluminescence material with emissive additives, also known as dyes. Then, the host material nonradiatively transfers its energy to the dye, which eventually emits light.[13] The other technique is based on stacking different organic electroluminescence materials. In this case, white light is generated by intermixing three primary colors or two complementary colors.[14−16] Another less often used concept is the deposition of a color-tunable filter on top of a white top-emitting OLED.[17] Such approaches are not beneficial because of considerable energy loss due to the reduction of the bandwidth of the spectrum. However, by precisely adjusting the

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Extending the environmental lifetime of unpackaged perovskite solar cells through interfacial design†

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Solution-processed oxo-functionalized graphene (oxo-G_1) is employed to substitute hydrophilic PEDOT:PSS as an anode interfacial layer for perovskite solar cells. The resulting devices exhibit a reasonably high power conversion efficiency (PCE) of 15.2% in the planar inverted architecture with oxo-G_1 as a hole transporting material (HTM), and most importantly, deploy the full open-circuit voltage (V_{oc}) of up to 1.1 V. Moreover, oxo-G_1 effectively slows down the ingress of water vapor into the device stack resulting in significantly enhanced environmental stability of unpackaged cells under illumination with 80% of the initial PCE being reached after 500 h. Without encapsulation, ~60% of the initial PCE is retained after ~1000 h of light soaking under 0.5 sun and ambient conditions maintaining the temperature beneath 30 °C. Moreover, the unsealed perovskite device retains 92% of its initial PCE after about 1900 h under ambient conditions and in the dark. Our results underpin that controlling water diffusion into perovskite cells through advanced interface engineering is a crucial step towards prolonged environmental stability.

Perovskite solar cells have attracted considerable research interest due to their remarkable PCEs exceeding the 20% benchmark and their potential to be manufactured by low-cost solution-processing technologies.[1–3] Device operational lifetime is the third corner of the magic triangle evaluating the performance potential of photovoltaic technologies, and this is of particular concern for the perovskite-based technology owing to its water soluble Pb-salt component.[4,5] Limited shelf as well as operational lifetime have been reported in the early stages of perovskite research and appeared to be one of the major roadblocks towards further driving this technology.[6] The precise degradation mechanism of perovskites in the presence of water is still under discussion. Previous studies have reported the loss of methyl-amine and the formation of yellowish PbI_2, while more recent studies rather suggest the partially reversible formation of $(CH_3NH_3)_4PbI_6{:}H_2O$ hydrate complexes as an intermediate step.[7,8] In addition, oxygen has been found to have only little effect on the degradation of perovskite devices.[8]

To address the stability issue of the perovskite solar cells, many efforts have recently been made. For example, several photo- or moisture-stable perovskite materials such as $(C_6H_5(CH_2)_2NH_3)_2(CH_3NH_3)_2[Pb_3I_{10}]$, $FA_{1-x}Cs_xPbI_3$ and $(CH_3NH_3Pb(SCN)_2)$ have been developed.[9–11] Recently, it has also been suggested that cross-linking perovskite grains with phosphonic acid ammonium derivatives may further decrease the moisture sensitivity of perovskite devices.[12]

A technically straightforward possibility to guarantee long-living perovskite devices is to provide a water and humidity dense package by using barriers and adhesives with a low water vapor transmission rate (WVTR).[13,14] Hydrophobic carbon nanotubes/poly(methyl methacrylate) composites and Teflon have been used as effective barriers to slow down the ingress of moisture and the extended lifetime of perovskite cells are observed.[13] In 2014, Han *et al.* employed a carbon layer as a back contact and a water-retaining layer for HTM-free perovskite solar cells. The resulting device exhibited a certified PCE of 12.8% and excellent stability under light soaking.[15] In another study by Wei *et al.*, a free-standing flexible carbon film was employed as the cathode of HTM-free perovskite solar cells, obtaining a PCE of up to 13.53% and good device stability.[16] Li

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Exploring the Limiting Open-Circuit Voltage and the Voltage Loss Mechanism in Planar $CH_3NH_3PbBr_3$ Perovskite Solar Cells

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Perovskite solar cells based on $CH_3NH_3PbBr_3$ with a band gap of 2.3 eV are attracting intense research interests due to their high open-circuit voltage (V_{oc}) potential, which is specifically relevant for the use in tandem configuration or spectral splitting. Many efforts have been performed to optimize the V_{oc} of $CH_3NH_3PbBr_3$ solar cells; however, the limiting V_{oc} (namely, radiative V_{oc}:$V_{oc,rad}$) and the corresponding ΔV_{oc} (the difference between $V_{oc,rad}$ and V_{oc}) mechanism are still unknown. Here, the average V_{oc} of 1.50 V with the maximum value of 1.53 V at room temperature is achieved for a $CH_3NH_3PbBr_3$ solar cell. External quantum efficiency measurements with electroluminescence spectroscopy determine the $V_{oc,rad}$ of $CH_3NH_3PbBr_3$ cells with 1.95 V and a ΔV_{oc} of 0.45 V at 295 K. When the temperature declines from 295 to 200 K, the obtained V_{oc} remains comparably stable in the vicinity of 1.5 V while the corresponding ΔV_{oc} values show a more significant increase. Our findings suggest that the V_{oc} of $CH_3NH_3PbBr_3$ cells is primarily limited by the interface losses induced by the charge extraction layer rather than by bulk dominated recombination losses. These findings are important for developing strategies how to further enhance the V_{oc} of $CH_3NH_3PbBr_3$-based solar cells.

1. Introduction

Solid-state perovskite solar cells that utilize methylammonium lead halide ($CH_3NH_3PbX_3$, X = I, Br, or Cl) as the light absorber have been attracting extensive interest as a next-generation photovoltaic technology since 2012.[1] $CH_3NH_3PbBr_3$ perovskite solar cells have attracted less attention than the iodide homologous. The relatively wide band gap of 2.3 eV limits the usable spectral range for singe junction solar cells, and according to the Shockley–Queisser model the photocurrent is expected to be below 9.7 mA cm^{-2}.[2] However, a relatively high V_{oc} of 1.4–1.5 V was reported, which makes this material system a great candidate for applications such as tandem configuration or other systems requiring spectral splitting.[2–7]

Significant efforts were undertaken to investigate and optimize the V_{oc} of $CH_3NH_3PbBr_3$ solar cells.[2–9] Engineering advanced hole transport layers (HTL) such as carbon nanotubes,[2] 2,2′,7,7′-tetrakis(*N*,*N*-di-*p*-methoxyphenyl-amine)-9,9′-spiro-bifluorene (spiro-OMeTAD),[5,7] poly (indenofluoren-8-triarylamine) (PIF8-TAA),[3,4] and 4,4-bis(*N*-carbazolyl)-1,1-biphenyl (CBP)[6] resulted in V_{oc} within a range of 1.4–1.5 V for solution-processed perovskite solar cells. Sheng et al. demonstrated a high V_{oc} of 1.45 V using the architecture TiO_2/$CH_3NH_3PbBr_3$/spiro-OMeTAD via a vapor-assisted depositon.[7] Kim et al. modified the TiO_2 surfaces with carboxyl groups and employed no HTL for $CH_3NH_3PbBr_3$ solar cells, producing a V_{oc} of 1.37 V.[8] Dymshits et al. reported a V_{oc} of 1.35 V for Al_2O_3/$CH_3NH_3PbBr_3$ perovskite solar cells without HTL.[9] These studies focused more on the V_{oc} improvement via interface engineering and via optimizing the $CH_3NH_3PbBr_3$ film quality. Despite significant progress toward unraveling the V_{oc} limitation of $CH_3NH_3PbBr_3$ solar cells, the limiting V_{oc} ($V_{oc,rad}$) is still unknown to the best of our knowledge. Besides,

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Applied Physics B
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Photoluminescence properties of thermographic phosphors YAG:Dy and YAG:Dy, Er doped with boron and nitrogen

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Abstract This paper investigates Dy^{3+}-doped and Dy^{3+}, Er^{3+}-co-doped yttrium aluminum garnets (YAG) with the admixture of boron nitride with the aim of using them as efficient thermographic phosphors at high temperatures. The phosphors were synthesized using a conventional high-temperature solid-state method. The influence of two fluxes, B_2O_3 and LiF/NH_4F, and the effect of activator and coactivator concentrations were investigated. Additionally, the effect of B^{3+} and N^{3-} substituting for Al^{3+} and O^{2-} ions, respectively, in the YAG:Dy^{3+} co-doped with Er^{3+} was studied for the first time. The changes in the host lattice led to a much stronger photoluminescence compared with the samples without B^{3+} and N^{3-} substitution. The admixture of BN also improves the thermal sensitivity of the YAG:Dy and YAG:Dy, Er thermographic phosphors.

1 Introduction

Phosphor thermometry is based on the correlation of photoluminescence (PL) properties of phosphors with temperature. This technique has a number of advantages compared to standard IR thermography. By using phosphor thermometry, temperature can be analyzed with non-contact measurement extensively and instantaneously with high sensitivity and accuracy. This technique has, therefore, been used for surface thermometry in gas turbines [1, 2] and engines [3] as well as for temperature analyses on gaseous flows [4–8]. In several cases, measurable signals and high chemical stability of phosphors at temperatures higher than 1200 K are required. One of the best phosphors for the high temperature range is $Y_3Al_5O_{12}$ (YAG) garnet doped with rare earth (RE^{3+}) ions [1], especially YAG:Dy [15, 19], which according to Cates et al. [13], shows measurable luminescence at 1705 °C.

Generally, the host lattice $Y_3Al_5O_{12}$ is well suited for the development of optical materials for different applications. Various rare earth dopants including Ce, Tb, Eu, Nd and Dy have been incorporated into YAG to control the phosphor luminescence. Single crystals and single crystalline films (SCF) of YAG, doped with Ce^{3+} and Pr^{3+} ions, are used as cathodoluminescent screens [9] and scintillators for visualization of X-ray images [10]. Crystals and SCF of Nd^{3+}-, Er^{3+}-, and Yb^{3+}-doped YAG are well-known laser media with laser action in the infrared range [11]. Dy^{3+}-, Sm^{3+}-, and Tm^{3+}-doped YAG phosphors have been used for thermographic applications [12–16]. Thermographic phosphors (TP) have to survive in high-temperature environment, and their temperature-dependent fluorescence characteristics such as emission wavelength, peak intensity ratio, or decay time can be calibrated for temperature measurements [17–20]. Modification of the host matrix allows to improve the thermographic properties. For example, Hansel et al. [21] substituted 50 % of the aluminum in YAG:Ce ($(Y_{1-x}Ce_x)_3Al_5O_{12}$) with gallium to produce a low-temperature TP, i.e., YAGG:Ce $(Y_{1-x}Ce_x)_3(Al_{1-y}Ga_y)_5O_{12}$, where $x = 0.01$, 0.02 and $y = 0$, 0.5), using a solution combustion synthesis. They found that shortening of the luminescence lifetime of YAGG:Ce occurred at a lower temperature than in YAG:Ce, which shifted the useful measurement range. Wang et al.

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Enhancement of the Power Conversion Efficiency in Organic Photovoltaics by Unveiling the Appropriate Polymer Backbone Enlargement Approach

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Optoelectronic properties, supramolecular assemblies, and morphology variation of polymeric semiconductors are governed by six fundamental chemical features. These features are molecular weight, bond length alternation (BLA), planarity, aromatic resonance energy, substituents, and intermolecular interactions. Of these features the specific role of BLA in determining the performance of a polymeric semiconductor in practical technological applications is so far unknown. This study investigates this question and reports the novel finding that the optoelectronic, microscopic (supramolecular packing), and macroscopic (morphology variation and device performance) properties of model semiconducting polymers depend on the conjugated polymer backbone enlargement, which is directly related to the BLA. Extensive studies are performed in both single-component polymer films and their blends with fullerene derivatives. Understanding the specific structure-properties relations will lead to significant advancement in the area of organic electronics, since it will set new design rules toward further optimization of polymer chemical structures to enhance the device performances.

1. Introduction

Organic semiconductors (small molecules, oligomers, and polymers) are materials that obtain their unique optical and electronic properties often originate from a tailored chemical structure.[1–3] During the past few decades a vast number of organic semiconductors for organic light emitting diodes (OLEDs),[4] organic field effect transistors (OFETs),[5–7] and organic photovoltaics (OPVs)[8–10] have been developed and various chemical modifications are used in order to engineer and optimize the chemical structure toward enhanced device performance through the synergistic expertise of chemists, material scientists, physicists, and engineers. It is therefore evident that the enormous potential for practical applications from organic electronics increases the value of this research field.[11] Polymeric semiconductors represent the most challenging category from the class of the organic semiconductors. The ability to control and optimize their chemical structure for different optoelectronic applications involves many parameters such as: (i) molecular weight, (ii) bond length alternation (BLA), (iii) planarity, (iv) aromatic resonance energy (E_{Res}), (v) substituents, and (vi) intermolecular interactions.[8,12] Nowadays, the proper design of polymeric semiconductors has been focused on the way with which the optoelectronic properties of the polymers and the resulting device performance can be affected. For example, it is well understood how the role of the ionization energy of the donor (D) and the electron affinity of the acceptor (A) moieties in the backbone of donor–acceptor (D–A) conjugated polymers affect the positioning of

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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)

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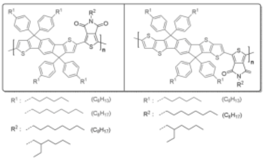
Systematic optimization of the chemical structure of wide-bandgap (≈2.0 eV) "donor–acceptor" copolymers consisting of indacenodithiophene or indacenodithieno[3,2-*b*]thiophene as the electron-rich unit and thieno[3,4-*c*]pyrrole-4,6-dione as the electron-deficient moiety in terms of alkyl side chain 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.



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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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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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Perovskite solar cells fabricated using dicarboxylic fullerene derivatives†

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Perovskite solar cells were first fabricated in dye sensitized solar cells. But also, perovskite hybrid solar cells were demonstrated to be among the most promising candidates within the emerging photovoltaic materials with their high power conversion efficiencies and low-cost fabrication. In this work, we design and synthesize a novel benzoic acid fullerene bis adduct material (BAFB) for use in perovskite hybrid organic–inorganic solar cells. The obtained maximum efficiency is reported to be 9.63% using a novel benzoic acid fullerene bis adduct (BAFB) for perovskite heterojunction solar cells.

Introduction

Perovskite heterojunction solar cells have attracted considerable attention recently because of their high solar cell efficiency besides their unique properties such as high absorption coefficient, excellent ambipolar charge mobility and small exciton binding energy.[1–10] Kojima *et al.*, first published liquid electrolyte dye sensitized solar cells of perovskite materials with 3.8% PCE solar cell efficiency.[1] Then, solid state dye sensitized solar cell efficiency was reported to be 10%. And today perovskite solar cells are known as highly efficient solar cells. The power conversion efficiencies (PCE) of organometal halide perovskite solar cells have increased from 3.8% to 20.1%. In other words, the power conversion efficiencies of perovskite solar cells have increased in the past five years. They are highly efficient for new generation organic photovoltaic technology because the efficiency of perovskite solar cells match the efficiency of commercialized crystalline Si solar cells.[11–19] The first perovskite solar cells were implemented in dye sensitized solar cells. But, perovskites have also been applied to heterojunction solar cells in low temperature solution processes. The configuration is quite similar to organic photovoltaic cells, which consist of easy solution processed fabrication techniques. Planar structured perovskite solar cells were fabricated with the efficiency of 10% by controlling interface engineering. The planar structure is a facile fabrication for low temperature solution processed solar cells.[20–25] The preparation of mesoporous TiO_2 is omitted in the planar heterojunction device structure.[25–30] In the planar structure, mesoporous TiO_2 replaces the hole transport PEDOT:PSS layer, and hole transport spiro-OMETAD replaces the PCBM layer. A perovskite light absorbing layer is sandwiched between the hole- and electron transporting layers in the planar heterojunction perovskite solar cells. It is very important to control the carrier behaviours and the interface in the whole perovskite solar cells.[30,31] The PEDOT:PSS layer is commonly used as the hole transport layer in heterojunction solar cells due to its good conductivity and solution processability. Although the mesoporous TiO_2 based solid state perovskite solar cells employ the most efficient solar cells, this type of solar cells needs a high temperature sintering process at 450 °C. This high temperature process effects the cost production of new generation solar cells and prevents the application in plastic substrates. For this reason, planar heterojunction perovskite solar cells supply an alternative approach for efficient perovskite solar cells with the sandwich geometry between the hole transport layer PEDOT:PSS and the electron transport layer [6,6]-phenyl-C_{61}-butyricacid methyl ester (PCBM). This alternative fabrication provides facile operation of solution processed perovskite solar cells. However, the alternative heterojunction perovskite solar cells have not yet reached the device efficiency of the conventional high temperature process. One developing step in planar perovskite heterojunction solar cells is to find a good electron acceptor fullerene material instead of the PCBM material to control the surface passivation of perovskite and interface properties.[32,33] For this reason, novel benzoic acid fullerene bis adducts (BAFB) were designed and synthesized for planar heterojunction perovskite solar cells in this paper. Optoelectronic, electrochemical and photovoltaic properties of novel fullerene materials have been studied. Novel benzoic acid fullerene bis adducts (BAFB) pay significantly more attention for engineering perovskite heterojunction solar cells to passivate the defects on the surface and

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ARTICLES

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Designing ternary blend bulk heterojunction solar cells with reduced carrier recombination and a fill factor of 77%

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In recent years the concept of ternary blend bulk heterojunction (BHJ) solar cells based on organic semiconductors has been widely used to achieve a better match to the solar irradiance spectrum, and power conversion efficiencies beyond 10% have been reported. However, the fill factor of organic solar cells is still limited by the competition between recombination and extraction of free charges. Here, we design advanced material composites leading to a high fill factor of 77% in ternary blends, thus demonstrating how the recombination thresholds can be overcome. Extending beyond the typical sensitization concept, we add a highly ordered polymer that, in addition to enhanced absorption, overcomes limits predicted by classical recombination models. An effective charge transfer from the disordered host system onto the highly ordered sensitizer effectively avoids traps of the host matrix and features an almost ideal recombination behaviour.

The combination of a broad understanding of material synthesis, device engineering and physical process control, combined with theoretical studies, has driven the organic photovoltaics (OPV) efficiency beyond the 10% milestone[1–9]. However, due to the narrow intrinsic absorption of polymers, full coverage of the solar spectrum with a single polymeric donor mixed with fullerene acceptor is fairly challenging. A promising strategy to overcome the absorption limitation is using the concept of ternary blends, typically consisting of two donor materials[10–16] with complementary absorption profiles and one acceptor material (or one donor and two acceptors)[17,18]. Importantly, the ternary organic solar cell concept features a simple device architecture and can readily be scaled up with cost-efficient equipment, which is in contrast to complex multi-junction solar cells[17–20]. Significant increases of the short-circuit current (J_{sc}) are achieved in ternary solar cells due to the additional absorption from the second donor material, resulting in remarkable performance improvements. Whereas for many ternary devices the open-circuit voltage (V_{oc}) normally scales with the sensitizer content between the V_{oc} values of two binary solar cells[21], the fill factor (FF) is often significantly reduced by the introduction of a third component with different physical and chemical properties. The formation of energetic or morphological traps as well as a disruption of the molecular packing in the host polymer[22] can degrade charge transport and increase recombination, leading to decreased fill factors[11].

Recently, high-mobility materials[14,23] have been introduced in the binary polymer:fullerene matrices as additives or morphology agents to improve the morphology and to facilitate charge transport. We have also demonstrated that the concept of ternary blends with over 50% sensitizer represents a promising route for controlling the recombination mechanism at low light levels[24]. In general, the FF in binary blends is limited by the competition between recombination and extraction of free charges[25]. The common approach to overcome those limitations is to design materials with novel properties forming an ideal morphology[3] or to optimize existing donors, that is, by purification and/or molecular weight[26].

In this work, we demonstrate a ternary organic solar cell with a record high FF of 77% and a high PCE of 8.6%. The photoactive layer consists of a host system of polythieno[3,4-b]-thiophene/benzodithiophene(PTB7):[6,6]-phenyl C70 butyric acid methyl ester (PC$_{70}$BM) and a sensitizer polymer of 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-benzothiadiazole)-5,5′-diyl](Si-PCPDTBT). To study the microstructure and transport of our ternary devices, we performed comprehensive characterization by employing different structural and optoelectrical techniques. Counterintuitive to classical sensitization concepts, where charges are transferred from the sensitizer to the host, we overcome charge recombination limitations on the host matrix by charge transfer to a highly ordered sensitizer, which provides ideal recombination behaviour. We choose a host amorphous polymer that provides highly efficient charge separation and introduce a second more crystalline polymer that facilitates charge transport, mimicking a three-phase morphology that is known for efficient device operation[27,28]. The energetic offset[29] between the highest occupied molecular orbital (HOMO) levels of the selected polymers results in spatial separation of charge carriers and significantly reduced recombination.

Device performance and recombination

We fabricated bulk heterojunction (BHJ) solar cells in an inverted configuration (Fig. 1a), keeping the polymer to PC$_{70}$BM ratio constant at 1:1.5. Figure 1b,c shows the chemical structures of

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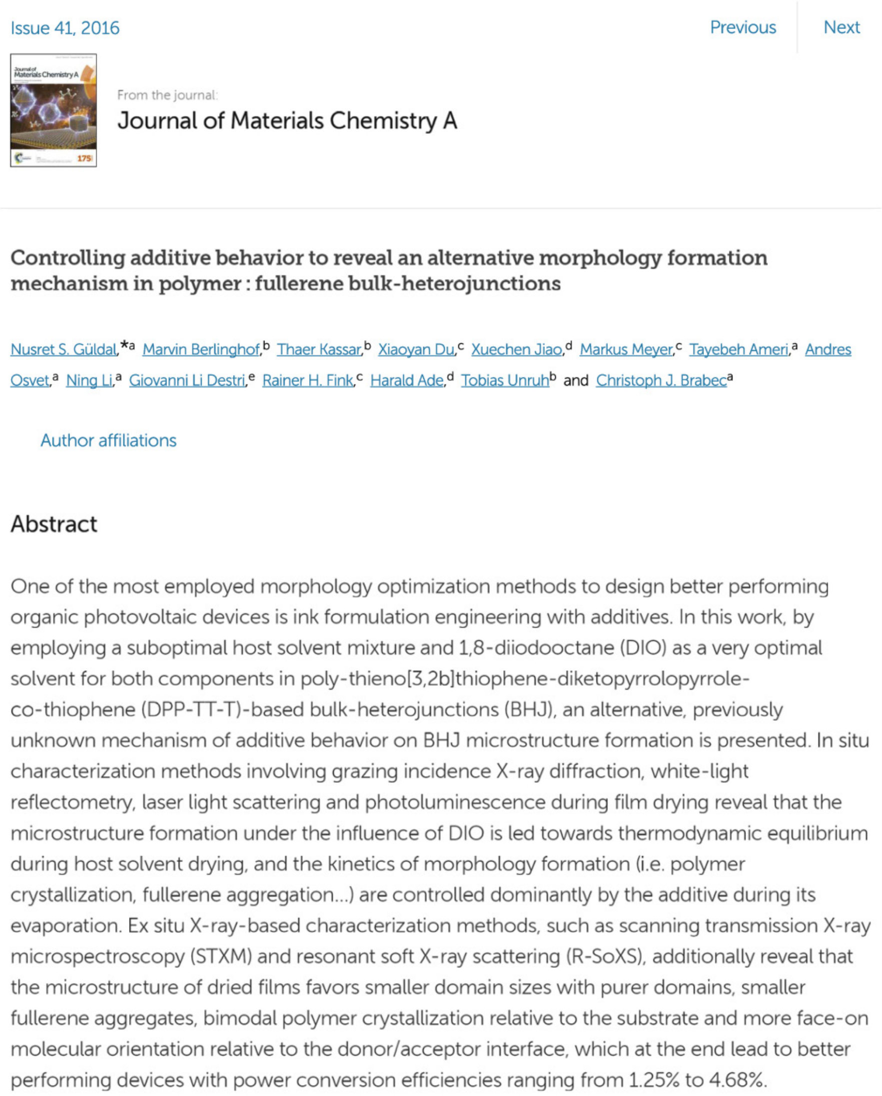

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From the journal:
Journal of Materials Chemistry A

Controlling additive behavior to reveal an alternative morphology formation mechanism in polymer : fullerene bulk-heterojunctions

Nusret S. Güldal,*[a] Marvin Berlinghof,[b] Thaer Kassar,[b] Xiaoyan Du,[c] Xuechen Jiao,[d] Markus Meyer,[c] Tayebeh Ameri,[a] Andres Osvet,[a] Ning Li,[a] Giovanni Li Destri,[e] Rainer H. Fink,[c] Harald Ade,[d] Tobias Unruh[b] and Christoph J. Brabec[a]

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Abstract

One of the most employed morphology optimization methods to design better performing organic photovoltaic devices is ink formulation engineering with additives. In this work, by employing a suboptimal host solvent mixture and 1,8-diiodooctane (DIO) as a very optimal solvent for both components in poly-thieno[3,2b]thiophene-diketopyrrolopyrrole-co-thiophene (DPP-TT-T)-based bulk-heterojunctions (BHJ), an alternative, previously unknown mechanism of additive behavior on BHJ microstructure formation is presented. In situ characterization methods involving grazing incidence X-ray diffraction, white-light reflectometry, laser light scattering and photoluminescence during film drying reveal that the microstructure formation under the influence of DIO is led towards thermodynamic equilibrium during host solvent drying, and the kinetics of morphology formation (i.e. polymer crystallization, fullerene aggregation…) are controlled dominantly by the additive during its evaporation. Ex situ X-ray-based characterization methods, such as scanning transmission X-ray microspectroscopy (STXM) and resonant soft X-ray scattering (R-SoXS), additionally reveal that the microstructure of dried films favors smaller domain sizes with purer domains, smaller fullerene aggregates, bimodal polymer crystallization relative to the substrate and more face-on molecular orientation relative to the donor/acceptor interface, which at the end lead to better performing devices with power conversion efficiencies ranging from 1.25% to 4.68%.

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Real-time evaluation of thin film drying kinetics using an advanced, multi-probe optical setup†

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Solution-processed organic photovoltaic devices are advantageous due to their low-cost large area manufacturing techniques, such as slot-die coating, gravure printing and roll-to-roll coating. The final microstructure of a polymer:fullerene bulk-heterojunction (BHJ) film is a fine interplay between solution thermodynamics (*e.g.* solubility, miscibility…) and kinetics (*e.g.* solvent evaporation, polymer ordering, phase separation…) during the drying process. In order to design better performing organic photovoltaic devices, gaining knowledge over the drying properties of polymer:fullerene thin films is essential. A novel *in situ* thin film drying characterization chamber, equipped with white-light reflectometry, laser light scattering and photoluminescence, is presented in combination with grazing-incidence X-ray diffraction on two different polymer:fullerene bulk heterojunctions based on poly-(3-hexylthiophene-2,5-diyl) (P3HT) and polythieno[3,2*b*]thiophene-diketopyrrolopyrrole-*co*-thiophene (DPP-TT-T) polymers. With photoluminescence applied for the first time as an *in situ* method for such drying studies, these single-chamber measurements track the fine interplay between thermodynamics and kinetics of thin film drying and provide invaluable information on solution behavior and microstructure formation.

1. Introduction

Solution-processed organic electronics benefit from their low-cost large area manufacturing techniques, such as slot-die coating, gravure printing and roll-to-roll coating.[1,2] Organic semiconductors in the form of thin films are extremely sensitive to processing conditions, which lead to different microstructures, subsequently affecting performance. An optimized polymer:fullerene bulk-heterojunction (BHJ) is a finely mixed, yet phase separated network, consisting of a conjugated polymer as a donor and a fullerene-derivative as an acceptor. It has a delicate morphology that is affected by the solvent choice, coating conditions and post-treatments, such as thermal annealing and solvent annealing.[3–6] The final microstructure of a BHJ film is determined by the interplay between thermodynamics (*e.g.* solubility, miscibility…) and kinetics (*e.g.* solvent evaporation, polymer ordering, phase separation…) during the drying process.[7,8] Therefore, gaining knowledge over the drying properties of polymer/fullerene thin films and correlating this information with the performance of lab-scale BHJs are essential in order to design better performing organic photovoltaic devices and transfer the manufacture protocols to large scale production.

Over the past decade, a considerable amount of *in situ* characterization methods has been used to study drying dynamics and microstructure evolution of BHJs.[9] One of the most popular methods is white-light/laser reflectometry, using which the evolution of drying film thickness can be determined.[7,8,10–18] Instead of reflectometry, some investigations have employed spectroscopic ellipsometry (SE), which is more sensitive to sub-nanometer regions, allowing the user to probe final stages of thin film drying.[19–21] Additionally, laser light and X-ray scattering techniques are used either as stand-alone methods or in combination with other optical methods. While laser light scattering has been used as a tool to investigate liquid–liquid phase separation in organic blends, grazing-incidence X-ray scattering, with its wide (GIWAXS) and small angle (GISAXS) forms, has become a very powerful technique to investigate periodic ordering and domain formation in organic thin films, respectively.[10,12,18,22,23]

So far, spin coating has been one of the most favoured casting methods to study *in situ* morphology formation due to its importance and prevalence in lab-scale organic film fabrication.[10,16–19,24]

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X-RAY IMAGING

Perovskites target X-ray detection

Single crystals of perovskites are currently of interest to help fathom fundamental physical parameters limiting the performance of perovskite-based polycrystalline solar cells. Now, such perovskites offer a technology platform for optoelectronic devices, such as cheap and sensitive X-ray detectors.

Wolfgang Heiss and Christoph Brabec

In the last few years researchers have exploited polycrystalline organic–inorganic hybrid perovskite semiconductors to boost the efficiency of solution-processed thin-film solar cells to values[1,2] that are beaten only by elaborate devices based on single-crystal materials.

X-ray radiation is detected by the conversion of high-energy X-ray photons either into light, by making use of scintillating materials, or directly into an electrical signal, by making use of so-called direct converters. Both approaches have their limitations, at least in pixelated detector arrays. Scintillator-based detector arrays have a limited resolution due to a lateral spread of the scintillated light within the converting layer. In contrast, direct converters, which are generally amorphous or polycrystalline semiconductors, are limited in their time response, causing effects such as ghosting. Perfect direct converters would be single crystals, which are, however, expensive and cannot be grown in arbitrary sizes.

Writing in *Nature Photonics*, Haotong Wei *et al.* now describe the application of perovskite single crystals as X-ray detectors[3], with comparable or even superior properties than those obtained with the established high-vacuum crystal-growth techniques, such as CdZnTe. The high performance of the X-ray detectors is enabled by the recently developed simple and fast solution-based growth methods for perovskite single crystals[4], providing crystals with dimensions up to 2 inches (ref. 5), with extremely low defect densities[6], and long electron–hole diffusion lengths[7]. The methylammonium lead tribromide ($MAPbBr_3$) single-crystal X-ray detectors demonstrated by Wei *et al.* exhibit a record mobility-lifetime product of 1.2×10^{-2} cm^2 V^{-1} and a collection efficiency of 16.4% for irradiation from an X-ray source providing a continuum of photon energies up to 50 keV.

X-ray detectors find applications in various fields, such as medical diagnostics, non-destructive testing of industrial products, and security inspection. These applications rely on the partial transparency of the object of interest for electromagnetic radiation in the energy range between 1 and 120 keV. While the transmissibility in the X-ray spectral region is of utmost importance for all these applications, it represents a serious problem for radiation detection. Thus, X-ray detectors are either bulky in their dimensions, such as gas-chamber detectors, or should consist of materials containing heavy elements, because the X-ray absorbance is proportional to the atomic number of the element to the power of four. The latter condition is fulfilled by typical scintillator materials (for instance CsI and $CdWO_4$) and by polycrystalline

Energy Science & Engineering

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RESEARCH ARTICLE

Automatized analysis of IR-images of photovoltaic modules and its use for quality control of solar cells

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Keywords
Imaging, IR-thermography, PV, quality control, segmentation, solar cell

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Abstract

It is well known that the performance of solar cells may significantly suffer from local electric defects. Accordingly, infrared thermography (i.p. lock-in thermography) has been intensely applied to identify such defects as hot spots. As an imaging method, this is a fast way of module characterization. However, imaging leads to a huge amount of data, which needs to be investigated. An automatized image analysis would be a very beneficial tool but has not been suggested so far for lock-in thermography images. In this manuscript, we describe such an automatized analysis of solar cells. We first established a robust algorithm for segmentation (or recognition) for both, the PV-module and the defects (hot spots). With this information, we then calculated a parameter from the IR-images, which could be well correlated with the maximal power (P_{mpp}) of the modules. The proposed automatized method serves as a very useful foundation for faster and more thorough analyses of IR-images and stimulates the further development of quality control on solar modules.

Introduction

Energy supply by renewable sources such as solar modules (PV) will be a key issue for societies for the next decades. Common solar cells of the "first generation" (based on Silicon) contribute significantly to the electricity generation in various countries already today [1]. The success story of PV was heavily promoted by decreasing silicon-PV prices. However, solar cells based on thin film absorbers, such as CIGS, CdTe, or organic photovoltaics (OPV), start to gain larger parts of the market share. For illustration, about 10% of the installed modules today are based on thin film technology [2]. This is very promising as thin film solar modules have a strong potential for further substantial decrease in price, such enabling a further increase in green electricity production.

Solar cells based on organic compounds are definitely one of the most thrilling options when aiming for a huge decrease in production costs. One key aspect here is the possibility to print organic solar cells in large scale, which would decrease strongly the price of OPV. While the production of silicon PV is a rather mature process,

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Morphological and electrical control of fullerene dimerization determines organic photovoltaic stability†

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Fullerene dimerization has been linked to short circuit current (J_{sc}) losses in organic solar cells comprised of certain polymer–fullerene systems. We investigate several polymer–fullerene systems, which present J_{sc} loss to varying degrees, in order to determine under which conditions dimerization occurs. By reintroducing dimers into fresh devices, we confirm that the photo-induced dimers are indeed the origin of the J_{sc} loss. We find that both film morphology and electrical bias affect the photodimerization process and thus the associated loss of J_{sc}. In plain fullerene films, a higher degree of crystallinity can inhibit the dimerization reaction, as observed by high performance liquid chromatography (HPLC) measurements. In blend films, the amount of dimerization depends on the degree of mixing between polymer and fullerene. For highly mixed systems with very amorphous polymers, no dimerization is observed. In solar cells with pure polymer and fullerene domains, we tune the fullerene morphology from amorphous to crystalline by thermal annealing. Similar to neat fullerene films, we observe improved light stability for devices with crystalline fullerene domains. Changing the operating conditions of the investigated solar cells from V_{oc} to J_{sc} also significantly reduces the amount of dimerization-related J_{sc} loss; HPLC analysis of the active layer shows that more dimers are formed if the cell is held at V_{oc} instead of J_{sc}. The effect of bias on dimerization, as well as a clear correlation between PL quenching and reduced dimerization upon addition of small amounts of an amorphous polymer into PC60BM films, suggests a reaction mechanism *via* excitons.

Broader context

Organic photovoltaics (OPV) enable light weight, flexible and semi-transparent devices with the potential for large scale power production. After a recently established world record of 11.5% power conversion efficiency for single junction organic bulk heterojunction solar cells and amplified interest in applications like building integrated OPV, the device stability is turning into key factor for the success of this technology. While highly crystalline donor polymers with relatively pure fullerene phases currently achieve the highest efficiencies, these pure fullerene phases can be prone to dimerization that causes performance losses. We investigate a wide range of polymer:fullerene blend systems and demonstrate how dimerization can be controlled by tuning the morphology of fullerene domains, leading to improved solar cell stability.

Introduction

Light induced dimerization of PC60BM[1,2] has been shown to cause severe short circuit current (J_{sc}) losses of organic photovoltaic (OPV) cells during operation in a few cases.[3,4] In apparent contradiction the most studied OPV system,[5] optimized P3HT:PC60BM devices, do not suffer significant dimerization-related J_{sc} losses.[6] To understand why fullerene dimerization causes severe performance losses in some cases, but is not

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ARTICLE

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High-efficiency and air-stable P3HT-based polymer solar cells with a new non-fullerene acceptor

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Solution-processed organic photovoltaics (OPV) offer the attractive prospect of low-cost, light-weight and environmentally benign solar energy production. The highest efficiency OPV at present use low-bandgap donor polymers, many of which suffer from problems with stability and synthetic scalability. They also rely on fullerene-based acceptors, which themselves have issues with cost, stability and limited spectral absorption. Here we present a new non-fullerene acceptor that has been specifically designed to give improved performance alongside the wide bandgap donor poly(3-hexylthiophene), a polymer with significantly better prospects for commercial OPV due to its relative scalability and stability. Thanks to the well-matched optoelectronic and morphological properties of these materials, efficiencies of 6.4% are achieved which is the highest reported for fullerene-free P3HT devices. In addition, dramatically improved air stability is demonstrated relative to other high-efficiency OPV, showing the excellent potential of this new material combination for future technological applications.

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JOURNAL OF APPLIED PHYSICS **120**, 113102 (2016)

Numerical study of plasmonic absorption enhancement in semiconductor absorbers by metallic nanoparticles

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We are studying the influence of spherical silver nanoparticles (AgNP) in absorbing media by numerically solving the Maxwell's equations. Our simulations show that the near-field absorption enhancement introduced by a single AgNP in the surrounding medium is increasing with the growing particle diameter. However, we observe that the relative absorption per particle volume is on a similar level for different particle sizes; hence, different numbers of particles with the same total volume yield the same near-field absorption enhancement. We also investigate the effect of non-absorbing shells around the AgNP with the conclusion that even very thin shells suppress the beneficial effects of the particles noticeably. Additionally, we include AgNP in an organic solar cell at different vertical positions with different particle spacings and observe the beneficial effects for small AgNP and the scattering dependent performance for larger particles. *Published by AIP Publishing.*
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I. INTRODUCTION

Photovoltaics (PV) plays a crucial role in the current transition from fossil and nuclear energy sources to more environmentally friendly renewable energies. The most commonly used PV devices are based on polycrystalline silicon wafers with active layer thicknesses up to 300 μm. To reduce the production costs, thin-film solar cells with active layer thicknesses of only $\sim$1 μm have been developed, often employing amorphous silicon, GaAs, CdTe, and other expensive and rare materials. Another promising thin-film solar cell technology is organic photovoltaics (OPVs). Since all the constituting layers can be processed from solution-processable materials, OPV offers the possibility of cost reduction by a large-area roll-to-roll production, using the established printing techniques. The current record efficiency of OPV is 11.5%.[1]

Due to the low charge-carrier mobility of the organic semiconductors, the thickness of the absorber layer is typically in the order of 100 nm. This results in non-optimized absorption of the incident light. In other thin-film solar cells, scattering at rough interfaces is an effective and well-understood method to increase the path length and thus the absorption. However, the dimensions of such a textured interface have to be in the order of the wavelength of the incident light or larger, and therefore larger than the thickness of the organic absorber layer. This requirement makes them unsuitable for OPV due to frequent shunting of the devices.

A more promising strategy to increase the performance of OPVs is to increase light absorption by utilizing scattering and plasmonic effects from metallic nanoparticles (NPs) with sizes far below the wavelengths of the incident light. Often the NPs are embedded into the layers surrounding the active absorber layer.[2–6] Then, of course, the plasmonic near-field enhancement cannot play a major role and only the scattering effects of the particles are used. But performance enhancements of OPVs utilizing the plasmonic effects from metallic NPs have been reported in literature.[2,6–10]

The excitation of the localized surface plasmons (LSPs) on metallic NPs results in an enhancement of the electromagnetic field in the direct vicinity of the particles. The origin of this effect is the oscillation of the electron cloud inside the metallic particles caused by the electric field of the incident light, shown in Figure 1.

With the electric field intensity being directly proportional to the energy absorbed by the medium and hence generation of excitons, this enhancement of the electric field can result in a better performance of the solar cell. The strength and the spectral shape of the plasmonic resonance depend on the diameter and shape of the metallic particle as well as on the optical constants of both the particle and the surrounding medium. In particular, the resonance peak shifts towards longer wavelengths with increasing particle size.[11]

Experimentally, it is extremely difficult to measure the near field and the absorption enhancement of a single particle inside a medium. Numerical simulations are therefore an ideal tool to accurately evaluate these effects. The analytical models utilizing the Mie theory are one possible method. Nevertheless, these models are restricted to specific, simple setups, like single particles or core-shell particles.[12] Since we are not only interested in the pure near-field of the particle but also in the scattering effect of particles incorporated in whole cells, a more sophisticated method is required. For this purpose, we use a variant of the finite-difference

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Overcoming the Interface Losses in Planar Heterojunction Perovskite-Based Solar Cells

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Perovskites have recently drawn tremendous research interest as they have demonstrated increased power conversion efficiencies (PCEs) of up to 20%,[1] which is getting more and more close to its inorganic, multi-crystalline counterparts like silicon, copper indium gallium (di)selenide (CIGS) or CdTe-based solar cells.[2] Different device configurations including mesoporous (regular and inverted structure) and planar (regular and inverted structure) architectures successfully demonstrated good device performance in combination with reliable perovskite processing.[3–7] In terms of up scaling towards roll-to-roll production, a low temperature, planar heterojunction device architecture would be most desired as this is the most simple and reliable architecture for solar cell processing.[8] However, till today, the ultimate intrinsic losses of the planar heterojunction architecture were not analyzed sufficiently to understand whether this architecture is competitive in terms of performance and processing.

Quite different from organic semiconductors, the ambipolar carrier diffusion lengths of perovskite semiconductors are large enough allowing to utilize the planar heterojunction with charge selective interfaces.[9–12] One interesting aspect of the planar architecture is the potential lower processing temperature as compared to the mesoporous metal-oxide-based electrodes.[13] However, the planar structure perovskite devices generally suffer from a series of deficiencies in the first place the hysteresis effect, which induces inconsistent device performance between the two different scan directions.[14–16] Although the origin of such hysteresis effect is still under debate, one of the potential explanations is the ion migration process in the device during measuring current–voltage characteristics. Grätzel group reported that charge carrier collection efficiencies strongly depend on the built-in potential.[17] They believed that ions tend to accumulate at the interfaces of the electrodes leading to a screening effect, thus decreasing the charge collection efficiency in a planar perovskite solar cell employing TiO_2 as electron transporting layer. Another proposal suggests that due to the possible ferroelectric properties of perovskite, when bias is applied on the device, a fast polarization of the material may occur. However, Barnes group reported that the time scale of ferroelectric domain relaxation within a device is roughly 0.1–1 ms, which is much faster than most observed hysteresis, thus questioning this explanation.[18] The slow trapping or detrapping of charges in electronic interface states is the third explanation. In a recent paper from Huang et al., they demonstrated that the hysteresis effect may origin from surface states trapping charge carriers at the surfaces and grain boundaries of the perovskite materials.[19] By the deposition of Phenyl-C61-butyric acid methyl ester (PCBM) layers on top of perovskite, a planar configuration consisting of ITO(Indium tin oxide)/Poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS)/Perovskite/PCBM/C_{60}/2,9-dimethyl-4,7-diphenyl-1,10-phenanthroline(BCP)/Al successfully eliminates photocurrent hysteresis. PEDOT:PSS is very well known and accepted by the organic PV community, and has its benefits for the perovskite technology like good reproducibility and no hysteresis, but is causing up to 200 mV more open circuit

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Hydrogen-Bonded Organic Semiconductors as Stable Photoelectrocatalysts for Efficient Hydrogen Peroxide Photosynthesis

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Research on semiconductor photocatalysts for the conversion of solar energy into chemical fuels has been at the forefront of renewable energy technologies. Water splitting to produce H_2 and CO_2 reduction to hydrocarbons are the two prominent approaches. A lesser-known process, the conversion of solar energy into the versatile high-energy product H_2O_2 via reduction of O_2 has been proposed as an alternative concept. Semiconductor photoelectrodes for the direct photosynthesis of H_2O_2 from O_2 have not been applied up to now. Photoelectrocatalytic oxygen reduction to peroxides in aqueous electrolytes by hydrogen-bonded organic semiconductor is observed photoelectrodes. These materials have been found to be remarkably stable operating in a photoelectrochemical cell converting light into H_2O_2 under constant illumination for at least several days, functioning in a pH range from 1 to 12. This is the first report of a semiconductor photoelectrode for H_2O_2 production, with catalytic performance exceeding prior reports on photocatalysts by one to two orders of magnitude in terms of peroxide yield/catalyst amount/time. The combination of a strongly reducing conduction band energy level with stability in aqueous electrolytes opens new avenues for this widely available materials class in the field of photo(electro) catalysis.

1. Introduction

Oxygen reduction reactions (ORR) of dissolved O_2 in water are important in biology, fuel cells, other energy conversion devices, and many industrial processes.[1–4] ORR can be a single-electron reduction to the oxygen radical anion, a two-electron reduction to hydrogen peroxide, H_2O_2, or finally a four-electron reduction to H_2O. Of these, H_2O_2 represents a versatile, high energy[5] product, capable of participating in numerous further redox reactions and is an active species in a plethora of biological processes.[6] Conversion of solar irradiation to hydrogen peroxide has been proposed for energy storage.[5,7] Hydrogen peroxide is a preferred "green" oxidant for industrial chemistry, as its only products are H_2O and O_2. The incumbent anthraquinone oxidation industrial process for H_2O_2 synthesis, however, is far from green, employing high temperatures, noble metal catalysts, high-pressure hydrogenation with H_2, and large volumes of organic solvents. This motivates research to develop alternative processes for H_2O_2 synthesis.[8] Some inorganic semiconductors in colloidal form (notably ZnO and CdS) are known photocatalysts for photochemical O_2 reduction to H_2O_2 (in the presence of a sacrificial electron donor).[9–12] Recently, graphitic carbon nitrides (g-C_3N_4) have been found to photocatalyze reduction of O_2 to H_2O_2 with concurrent ethanol oxidation[13] or water oxidation.[14] Observation of photocatalytic generation of H_2O_2 by a semiconductor photocathode has never been reported. This approach is advantageous as it is a truly heterogeneous catalysis that is accompanied by the generation of photocurrent which can do additional work, thereby allowing the photocathode to be incorporated into a photoelectrochemical cell. In this paper, we have successfully demonstrated that an emerging class of organic semiconductors, hydrogen-bonded pigments, is suitable as catalytic semiconductor photocathodes for selective ORR to produce hydrogen peroxides in an unprecedented pH range with nearly two orders of magnitude higher catalytic activity compared with the best known H_2O_2-producing photocatalysts. Organic semiconductors, which have evolved over the past decades to be established materials for xerography[15] and light-emitting diodes,[16] are also promising for photovoltaics.[17,18] Due to limited stability in aqueous environments, especially under photoirradiation, they have been largely unexplored in aqueous (photo)electrochemistry applications. Aqueous photocathode behavior of the

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Polarons in Narrow Band Gap Polymers Probed over the Entire Infrared Range: A Joint Experimental and Theoretical Investigation

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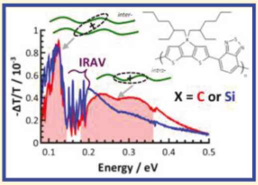
Supporting Information

ABSTRACT: We investigate the photoinduced absorption (PIA) spectra of the prototypical donor−acceptor polymer [2,6-(4,4-bis(2-ethylhexyl)-4H-cyclopenta[2,1-b;3,4-b′]dithiophene)-*alt*-4,7-(2,1,3-benzothiadiazole)] (C-PCPDTBT) and its silicon bridged variant Si-PCPDTBT over a spectral range from 0.07 to 1.5 eV. Comparison between time-dependent density functional theory simulations of the electronic and vibrational transitions of singlet excitons, triplet excitons, polarons, and bipolarons with the experimental results proves that the observed features are due to positive polarons delocalized on the polymer chains. We find that the more crystalline Si-bridged variant gives rise to a red-shift in the transition energies, especially in the mid-infrared (MIR) spectral range and furthermore observe that the pristine polymers' responses depend on the excitation energy. Blending with PCBM, on the other hand, leads to excitation-independent PIA spectra. By computing the response properties of molecular aggregates, we show that polarons are delocalized in not only the intra- but also the interchain direction, leading to intermolecular transitions which correspond well to experimental absorption features at the lowest energies.



Photons absorbed by organic materials commonly generate bound excitations which, in order to dissociate (e.g., in organic solar cells), require an energy offset that facilitates the splitting into free electrons and holes. Whereas in the simplest picture this involves a diffusion toward an interface (often between polymer and fullerene phases),[1,2] it has also been shown that long-range electron transfer, i.e., not involving diffusion processes, can lead to the formation of free carriers.[2] Given the low permittivity of organic materials (typically in the range of 2−4) the presence of charges leads to self-localization, structural relaxations, and polarization mechanisms generally described in the framework of the polaron theory.[3] Similarly to the initially formed singlet excitons and further species (including e.g. triplets and charge transfer states), polarons may be probed via optical experiments.[4,5]

Investigations of the photoinduced mid-infrared (MIR, ≈400−4000 cm^{-1}) response of semiconducting polymers date back to the 1980s.[6−9] The MIR spectra were rationalized in the framework of the Hückel and Su−Schrieffer−Heeger (SSH) models,[7,10] assigning observed transitions to long-lived species such as polarons or bipolarons. According to these models, charge carriers occupy states within the band gap of the polymer and thereby give rise to additional transitions: two polaron absorptions (namely P1 and P2) in the MIR and near-infrared (NIR, ≈4 000−12 500 cm^{-1}) spectral region, or one bipolaron transition (named BP1 or B1) in the NIR as depicted in Figure 1a. Despite several approximations, these schemes remained the picture of choice for analyzing photoinduced absorption (PIA) spectra in the MIR region for a long time. Only recently, an alternative scheme for the states occupied by charged species was proposed first for molecular semiconductors[11] and subsequently for conjugated polymers (Figure 1).[12]

All aforementioned models, however, account for only single-chain processes (i.e., intrachain), thus neglecting the possibility of interchain mechanisms. Around the year 2000, the effect of interchain delocalization on the PIA spectra of poly-3-hexylthiophene (P3HT) aggregates and crystallites was investigated.[4,13,14] It was reported that upon increasing the head-to-tail ratio in the polymer chains, i.e., from regiorandom (RRa-) to regioregular (RR-) P3HT, signals at lower energies emerged, which were attributed to interchain delocalized polarons (or "charge-transfer like" transitions). Still, P3HT is a homopolymer, whereas state-of-the-art polymers in organic

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Real-Time Investigation of Intercalation and Structure Evolution in Printed Polymer:Fullerene Bulk Heterojunction Thin Films

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The complex intermixing morphology is critical for the performance of the nanostructured polymer:fullerene bulk heterojunction (BHJ) solar cells. Time resolved in situ grazing incidence X-ray diffraction and grazing incidence small angle X-ray scattering are used to track the structure formation of BHJ thin films formed from the donor polymer poly(2,5-bis(3-hexadecylthiophen-2-yl)thieno[3,2-*b*]thiophene) with different fullerene derivative acceptors. The formation of stable bimolecular crystals through the intercalation of fullerene molecules between the side chains of polymer crystallites is investigated. Such systems exhibit more efficient exciton dissociation but lower photoconductance and faster decay of charges. On the basis of the experimental observations, intercalation obviously takes place before or with the formation of the crystalline polymer domains. It results in more stable structures whose volume remains constant upon further drying. Three distinct periods of drying are observed and the formation of unidimensional fullerene channels along the π-stacking direction of polymer crystallites is confirmed.

1. Introduction

Solution-processable bulk heterojunction (BHJ) organic solar cells exhibit a promising potential as inexpensive alternative to traditional inorganic photovoltaics through "roll-to-roll" printing on flexible materials.[1–5] On a laboratory scale devices with power conversion efficiencies exceeding 11% have been achieved.[4–7] These devices possess an active layer which consists of a blend of an electron-donating conjugated polymer and an electron-accepting fullerene derivative. The polymer is selected to absorb photons in the relevant range of the visible–UV spectrum. In this process, excitons are generated in the polymer. By diffusion, the excitons can reach the donor–acceptor interface at the polymer–fullerene phase boundary where they can dissociate into free charge carriers. Due to the short exciton mean diffusion length of about 5–10 nm in typical conjugated polymers,[8,9] the two phases need to be intermixed on the nanoscale which ensures an effective charge separation in such BHJ systems. Extraction of photo-generated electrons and holes before recombining requires donor/acceptor percolation pathways to facilitate charge carrier transport. From these considerations, it becomes obvious that the performance of a BHJ solar cell strongly depends on the interpenetrating morphology of the nanostructured active layer.[10,11]

BHJs were thought to be separated into domains of relatively pure polymer and pure fullerene phases.[12–15] Later it was found that fullerene derivatives can intercalate between the polymer side chains in some polymer:fullerene blends resulting in bimolecular crystals. Such intercalation affects performance and charge transport of the active layer.[16–18] Fullerenes in blends with intercalation fill all the space between the polymer side chains before forming its pure domains.[17] In this case, high fullerene concentrations are needed to achieve interconnected precipitated fullerene domains[19] which are essential for creating electron percolation paths and thus for device operation.[16] Intercalation increases the blend cohesion and resistance to mechanical failure.[20] The bimolecular

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A Series of Pyrene-Substituted Silicon Phthalocyanines as Near-IR Sensitizers in Organic Ternary Solar Cells

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An attractive method to broaden the absorption bandwidth of polymer/fullerene-based bulk heterojunction (BHJ) solar cells is to blend near infrared (near-IR) sensitizers into the host system. Axial substitution of silicon phthalocyanines (Pcs) opens a possibility to modify the chemical, thermodynamic, electronic, and optical properties. Different axial substitutions are already designed to modify the thermodynamic properties of Pcs, but the impact of extending the π-conjugation of the axial ligand on the opto-electronic properties, as a function of the length of the alkyl spacer, has not been investigated yet. For this purpose, a novel series of pyrene-substituted silicon phthalocyanines (SiPc-Pys) with varying lengths of alkyl chain tethers are synthesized. The UV–vis and external quantum efficiency (EQE) results exhibit an efficient near IR sensitization up to 800 nm, clearly establishing the impact of the pyrene substitution. This yields an increase of over 20% in the short circuit current density (J_{SC}) and over 50% in the power conversion efficiency (PCE) for the dye-sensitized ternary device. Charge generation, transport properties, and microstructure are studied using different advanced technologies. Remarkably, these results provide guidance for the diverse and judicious selection of dye sensitizers to overcome the absorption limitation and achieve high efficiency ternary solar cells.

1. Introduction

Over the past decade, bulk heterojunction (BHJ) solar cells based on polymer/fullerene blends have shown great potential to harvest solar energy in the most cost-effective possible manner.[1–6] Recently, the power conversion efficiencies (PCEs) over 10% have been reported based on mid or low band gap polymers which are able to harvest a broader fraction of the solar spectrum.[7–10] Addressing BHJ systems, most research efforts have been focused on blended material systems based on poly (3-hexylthiophene) (P3HT), and phenyl-C_{61}-butyric acid methyl ester ($PC_{61}BM$), as the electron donor and acceptor, respectively.[11–13] One of the drawbacks of P3HT is its limited light harvesting capability, as the whole band gap of > 1.9 eV can only absorbs a quarter of the total photons of the solar eradiation at best.[14] This leaves plenty of room for improvement of photocurrent by enhancing the spectral sensitivity in the visible as well as in the near-IR region of the spectrum.

To overcome absorption limitations in organic photovoltaic (OPV), several strategies are currently pursuing to achieve enhanced PCE. For example, extensive works have been performed to employ conjugated polymers with smaller band gap, which extend absorption into the near-IR and improve light harvesting.[15–19] The tandem concept, which involves stacking two or more cells with complementary absorption spectra in series or parallel connection, harvests photons at the highest possible potential.[20–22] Alternatively, the concept of ternary sensitization cells has been introduced, which uses a third component with different optical properties to act as a second donor or acceptor in BHJ solar cells.[23–29] Among them, dye sensitized ternary solar cells have already attracted significant attention because they are easy to adapt in ternaries in respective to microstructure compatibility and spectral sensitivity.[30–32]

Recently, Honda et al. studied ternary solar cells based on P3HT:$PC_{61}BM$ using bis (tri-n-hexylsilyl oxide) silicon phthalocyanine ($(3HS)_2$-SiPc) as sensitizer.[33] An increase of up to

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Effective Ligand Engineering of the Cu_2ZnSnS_4 Nanocrystal Surface for Increasing Hole Transport Efficiency in Perovskite Solar Cells

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Effective engineering of surface ligands in semiconductor nanocrystals can facilitate the electronic interaction between the individual nanocrystals, making them promising for low-cost optoelectronic applications. Here, the use of high purity Cu_2ZnSnS_4 (CZTS) nanocrystals as the photoactive layer and hole-transporting material is reported in low-temperature solution-processed solar cells. The high purity CZTS nanocrystals are prepared by engineering the surface ligands of CZTS nanocrystals, capped originally with the long-chain organic ligand oleylamine. After ligand removal, CZTS nanocrystals show substantial improvement in photoconductivity and mobility, displaying also an appreciable photoresponse in a simple heterojunction solar cell architecture. More notably, CZTS nanocrystals exhibit excellent hole-transporting properties as interface layer in perovskite solar cells, yielding power conversion efficiency (PCE) of 15.4% with excellent fill factor (FF) of 81%. These findings underscore the importance of removing undesired surface ligands in nanocrystalline optoelectronic devices, and demonstrate the great potential of CZTS nanocrystals as both active and passive material for the realization of low-cost efficient solar cells.

1. Introduction

Kesterite Cu_2ZnSnS_4 (CZTS) is considered as one of the high potential material systems for solar energy production considering its non-toxicity, direct bandgap (with the optimal bandgap of 1.5 eV, high absorption coefficient ($\approx 1 \times 10^4$ cm^{-1}), and excellent environmental stability. The conventional process for CZTS deposition is based on high vacuum processes which are highly capital intensive. Development of non-vacuum deposition processes may substantially reduce the production costs. These non-vacuum process such as spray pyrolysis,[1,2] electrodeposition,[3] sol–gel,[4] and nano-particles or colloidal route of synthesis,[5,6] are more attractive for scaling-up production.

Applications of colloidal semiconductor nanocrystals (NCs) range from bio-labeling to photocatalysis and photovoltaics, requiring a diversity of properties through controlled crystal synthesis. As our intended applications are optoelectronic devices, synthesized nanoparticles used to be optimized with respect to solubility but also with respect to conductivity. The conventional stabilization of individual colloidal NCs is done by attaching long-chain organic molecules to prevent agglomeration of NCs in solution. In case of CZTS oleic acid (OA), tri-n-octylphosphine (TOP), or oleylamine (OAm) are typically used[7,8] which are not optimal for application in optoelectronic devices due to the insulating nature of the ligands limiting the charge transport between the particles.[9–12] For instance, the utilization of OAm leads to the formation of a carbon-rich layer and was further found to limit the grain growth by developing a fine grained layer between the active layer and the Mo substrate during thermal annealing.[13–15] To avoid or reduce the probability of such undesired effects, bulky ligands should be

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Galvanic Exchange in Colloidal Metal/Metal-Oxide Core/Shell Nanocrystals

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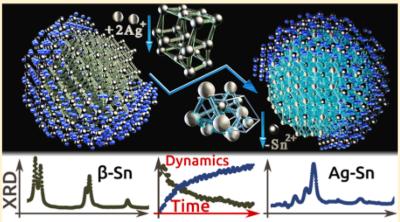
Supporting Information

ABSTRACT: While galvanic exchange is commonly applied to metallic nanoparticles, recently its applicability was expanded to metal-oxides. Here the galvanic exchange is studied in metal/metal-oxide core/shell nanocrystals. In particular Sn/SnO_2 is treated by Ag^+, Pt^{2+}, Pt^{4+}, and Pd^{2+}. The conversion dynamics is monitored by in situ synchrotron X-ray diffraction. The Ag^+ treatment converts the Sn cores to the intermetallic Ag_xSn ($x \sim 4$) phase, by changing the core's crystal structure. For the analogous treatment by Pt^{2+}, Pt^{4+}, and Pd^{2+}, such a galvanic exchange is not observed. This different behavior is caused by the semipermeability of the naturally formed SnO_2 shell, which allows diffusion of Ag^+ but protects the nanocrystal cores from oxidation by Pt and Pd ions.



INTRODUCTION

Galvanic replacement[1−14] and cation exchange reactions[15−23] similar to it represent simple and versatile tools to achieve nanoarchitectures and compositions of colloidal nanocrystals not readily accomplished by other methods.[8,24−27] Galvanic replacement has been applied to metal nanoparticles[1−9,25−27] and recently also to metal-oxide nanocrystals.[10] The former attracted a lot of attention due to their high potential for biomedical[4] as well as for surface enhanced Raman scattering applications,[5] whereas the latter have been demonstrated to exhibit good performance as anode materials for lithium ion batteries.[10] Since only certain intermetallic compounds can be produced by direct synthesis, often exploiting nonequilibrium processes,[28−31] the post growth treatment is an elegant alternative to produce intermetallic compound nanostructures, whose morphology can be tuned.[9,25−27]

Here the galvanic replacement method is expanded to metal/metal-oxide core/shell nanocrystals. Metal/metal-oxide nanocrystals based on Sn, Al, Fe, Ni, or Cu and covered by the corresponding oxide shells are synthesized for various applications, including plasmonics, photocatalysis, and electrochemical production of hydrogen, as well as magnetic targeting, magnetic resonance imaging, and near-infrared photothermal therapy.[32−38] In this study we focus our interest on Sn-based nanocrystals and their alloys, which are promising materials in lithium ion batteries.[39−44] In particular, spherical Sn/SnO_2 nanocrystals are exposed either to (i) Ag^+, (ii) Pt^{2+}, (iii) Pt^{4+}, or (iv) Pd^{2+} ions to study the formation of intermetallic alloys, and the influence of the oxide shell on the galvanic replacement reaction. Rather surprising results are obtained: For i, only the core material is heavily affected by the galvanic exchange, whereas the shell is almost fully retained. In cases ii−iv, no indications for any galvanic exchange reactions are observed. Condition i is further a special case because of the following: (a) The nanocrystal shape is preserved, which is commonly only the case in cation exchange reactions due to anion

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Industrially scalable and cost-effective Mn^{2+} doped $Zn_xCd_{1-x}S/ZnS$ nanocrystals with 70% photoluminescence quantum yield, as efficient down-shifting materials in photovoltaics†

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We present colloidally stable and highly luminescent $Zn_xCd_{1-x}S$:Mn/ZnS core–shell nanocrystals (NCs) synthesized *via* a simple non-injection one-pot, two-step synthetic route, which can be easily upscaled. A systematic variation of the reaction component, parameters and thickness of the ZnS shell yielded doped nanocrystals with a very high photoluminescence quantum yield (Φ_{pl}) of 70%, which is the highest value yet reported for these Mn-doped sulfide-semiconductor NCs. These materials can be synthesized with high reproducibility in large quantities of the same high quality, *i.e.*, the same Φ_{pl} using accordingly optimized reaction conditions. The application of these zero-reabsorption high quality NCs in the light conversion layers, deposited on top of a commercial monocrystalline silicon (mono-Si) solar cell, led to a significant enhancement of the external quantum efficiency (EQE) of this device in the ultraviolet spectral region between 300 and 400 nm up to *ca.* 12%. EQE enhancement is reflected by an increase in the power conversion efficiency (PCE) by nearly 0.5 percentage points and approached the theoretical limit (0.6%) expected from down-shifting for this Si solar cell. The resulting PCE may result in a BoM (bill of materials) cost reduction of app. 3% for mono-Si photovoltaic modules. Such small but distinct improvements are expected to pave the road for an industrial application of doped semiconductor NCs as cost-effective light converters for silicon photovoltaic (PV) and other optoelectronic applications.

Broader context

The low efficiencies of inorganic solar cells in the ultraviolet (UV) and blue spectral region are key factors which restrict their power conversion efficiency (PCE). A simple and reliable technological step to overcome these limitations, which can be easily introduced into the manufacturing process, is the coating of the cover glass or the solar cells/modules by a light-converting material with high absorption in the UV-blue, luminescence in the active solar cell region, and a high photoluminescence quantum yield/efficiency. The resulting conversion of UV/blue light to the active spectral region of the solar cell can improve PCE by several percentage points, especially in the case of thin-film solar cells based on $CuInGaSe_2$ or CdTe. Due to the already relatively high efficiency of the monocrystalline silicon (mono-Si) solar cells in the UV (about 45% at 300 nm) the expected improvement of the PCE of these cells is about 0.6 percentage points. Due to the high market share of the mono-Si modules, this improvement is expected to be nevertheless very profitable. To demonstrate the potential of this concept using the most promising type of light converters, that is, zero-reabsorption doped semiconductor quantum dots (QDs), we developed a simple non-injection one-pot, two-step synthetic route towards $Zn_xCd_{1-x}S$:Mn/ZnS core–shell nanocrystals showing a broad and efficient emission centered at 598 nm, which can be easily upscaled, and a simple coating technique to generate down shifting layers applicable to conventional mono-Si solar cells. With this approach, we could improve the efficiency of a commercial Si solar cell by up to *ca.* 12% in the UV spectral region which led to an enhancement of PCE by nearly 0.5 percentage points and will enable a cost reduction of *ca.* 3.3%. Our simple strategy is expected to encourage solar module manufacturers to also equip their photovoltaic modules with light converting layers and pave the road to a broader application of solar cells.

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Deciphering the Role of Impurities in Methylammonium Iodide and Their Impact on the Performance of Perovskite Solar Cells

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Solution-based perovskite solar cell fabrication typically involves rather complex processing sequences to yield highest performance. While most studies concentrate on the exploration of processing conditions, the purity levels of common perovskite precursor solutions have been investigated and a number of impurities that are critically important toward controlling the crystallization of perovskites are found. In this study, an in-depth chemical study of the possible impurities formed during CH_3NH_3I preparation is presented and their relevance on solar cell processing is revealed. A primary consideration is the chemical transformation of hypophosphorous acid, which plays the role of the stabilizer for HI. The detrimental role of the impurities is best demonstrated by comparing perovskite solar cell devices fabricated from impurity-free precursors versus precursors containing different concentrations of impurities. Most interestingly, it is revealed that a certain concentration of impurities is detrimental to the growth of large-grained crystals. $PbHPO_3$ nanoparticles, which are formed after hypophosphorous acid transformation, actually cause crystal domain growth through serving as a nucleation center. This study gives valuable insight into the rate determining steps of perovskite crystal growth and further provides the basis for developing reliable and reproducible high-performance recipes for perovskite solar cell processing.

1. Introduction

Organometallic halide perovskites $CH_3NH_3PbX_3$ (X = I, Br, Cl) have quickly become promising semiconductors for solar cell applications, reaching power conversion efficiencies up to 20%.[1–3] Development of the technology of perovskite-based solar cells requires precise control purity of the raw material and full understanding of the internal chemical process that occurs during precursor formation. A precise stoichiometric ratio of methylammonium iodide (CH_3NH_3I) and lead (II) iodide (PbI_2) plays an important role in the final perovskite film formation, thermal stability, morphology, and final solar cell performance.[4–6] Non-stoichiometric ratios with extra excess PbI_2 favor formation of larger perovskite domains that provide higher performance and stability of the final device.[3] In addition to stoichiometry, "quasi" colloidal particles[7] or reducing agent additives such as

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Highly efficient, large area, roll coated flexible and rigid OPV modules with geometric fill factors up to 98.5% processed with commercially available materials†

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Highly efficient, large area OPV modules achieving full area efficiencies of up to 93% of the reference small area cells are reported. The way to a no-loss up-scaling process is highlighted: photoelectrical conversion efficiencies of 5.3% are achieved on rigid modules and of 4.2% on flexible, roll coated ones, employing a commercially available photoactive material. Exceptionally high geometric fill factors (98.5%), achieved *via* structuring by ultrashort laser pulses, with interconnection widths below 100 μm are demonstrated.

Broader context

The achievement of high performances for solar modules can be considered one of the biggest challenges to be tackled in order to make printed photovoltaics suitable for industrial production and commercialization. Often the scientific community is solely focused on achieving the highest, record performances on small scale devices, disregarding the development of suitable up-scaling strategies to minimize the performance drop between single cells and modules. In this contribution the key factors for an ideal large area processing are addressed: optical and electrical simulations for the design of the geometry of the modules and the choice of the electrode materials; roll-to-roll printing and laser structuring demonstrating that losses between cells and modules can be as low as 7%. The use of halogen-free formulations and materials available in large quantities constitute as well an important step towards industrially sustainable processes.

1. Introduction

In recent years, printable photovoltaic technologies have been attracting the attention of the scientific community, due to their potentialities; in fact, solution processability constitutes a major advantage towards large scale, cheap, industrial production of solar cells. Furthermore, the rapid energy payback time of these technologies makes them of particular interest.[1] Despite the high efficiencies reported on lab scale devices, which recently surpassed 10% power conversion efficiency (PCE) for organic photovoltaics (OPV)[2] and 20%[3] for perovskite based ones, very little progress is shown towards up-scaling processing of solar cells.[4–8] Large area, roll-to-roll (R2R) processed solar cells and modules usually show a quite remarkable drop in efficiencies compared to small area, lab-produced hero cells,[9] highlighting the importance of the development of a stable, reliable production process which should allow a minimization of the performance losses. Recently we showed what are the guidelines for an optimal upscaling route for large area modules,[10] using a combination of optical simulations (transfer matrix formalism – TMF) and electrical simulations (finite element simulations – FEM): a loss in PCE of less than 10% should be achievable for opaque devices under optimized conditions. Generally this involves (i) a careful choice and optimization of the printing techniques, (ii) the development of halogen-free formulations allowing the achievement of the right morphology for the active layers, (iii) the development of a reliable, fast, high resolution patterning method for the monolithical interconnection of the cells in a module, the latest being of particular importance to minimize the size of the interconnection area which is not photoactive and thus is accountable as a loss. The ratio between the photoactive area and the total area of the module is usually referred to as the geometric fill factor (GFF).

In this report we performed optical simulations to quantify the losses induced by the change of electrode materials when going to up-scaled modules and compared them with experimental results. Then electrical simulations are carried out to assess the losses due to the monolithic interconnection of the cells in a module and are able to minimize them by choosing the appropriate layout. We will show how theoretical calculations can be matched with experimental results, yielding large area modules with PCEs of up to 90% of the reference hero cells by choosing high precision slot-die coating on a fully R2R compatible printing setup in combination with high precision,

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Effects of electron-withdrawing group and electron-donating core combinations on physical properties and photovoltaic performance in D-π-A star-shaped small molecules

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ABSTRACT

The first representatives of star-shaped molecules having 3-alkylrhodanine (alkyl-Rh) electron-withdrawing groups, linked through bithiophene π-spacer with electron-donating either triphenylamine (TPA) or *tris*(2-methoxyphenyl)amine (m-TPA) core were synthesized. The physical properties and photovoltaic performance of these novel molecules with 3-ethylrhodanine groups were comprehensively studied and compared to their full analogs having dicyanovinyl (DCV) units as the other type of well-known and frequently used acceptor groups. On one hand, the former demonstrate several advantages such as higher solubility and better photovoltaic performance in bulk-heterojunction (BHJ) organics solar cells (OSCs) as compared to the latter. Nevertheless, the former have slightly lower optical/electrochemical bandgaps and higher thermooxidation stability. On the other hand, molecules of both series based on m-TPA core along with higher solubility and higher position of HOMO energy levels have more pronounced tendency to crystalize as compared to the TPA-based molecules. Detailed investigation of the structure-property relationships for these series of molecules revealed that donor and acceptor unit combinations influence both charge generation and charge transport/recombination properties, as demonstrated by the ultrafast photoinduced absorption spectroscopy, space charge limited current measurements and transient photovoltage technique. These results give more insight how to fine-tune and predict physical properties and photovoltaic performance of small molecules having either alkyl-Rh or DCV units in their chemical structures and thus providing a molecular design guideline for the next generation of high-performance photovoltaic materials.

1. Introduction

Among all available renewable energy sources, solar energy appears to be the most promising primary energy source of the future [1]. Organic solar cells (OSCs) excel with low production costs, substrate and shape freedom, and the ability to manufacture lighter, highly flexible, and semitransparent devices, which open avenues for new application areas such as building integrated photovoltaics for sun shading and electricity generating glass facades [2,3]. Solution-processable small molecules for bulk heterojunction (BHJ) OSCs have attracted considerable attention in recent years because of their advantages of high purity, definite molecular

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Star-shaped D–π–A oligothiophenes with a tris(2-methoxyphenyl)amine core and alkyldicyanovinyl groups: synthesis and physical and photovoltaic properties†

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Synthesis of a series of star-shaped oligomers having a novel electron donating tris(2-methoxyphenyl)-amine (m-TPA) core, which is linked through a bithiophene or terthiophene π-bridge with electron-deficient alkyldicyanovinyl (alkyl-DCV) groups, is described. A comprehensive study of the oligomers revealed significant dependence of their physical properties, including absorption, molecular frontier energy levels, crystal packing, and melting and glass transition temperatures, upon the chemical structure. A comparison of their photophysical properties to the nearest analog having the common dicyanovinyl (DCV) groups demonstrated a number of benefits to use alkyl-DCV units for the design of donor–acceptor small molecules: higher solubility, increased electrochemical stability, better photovoltaic performance, and possibility to control the relative physical and photovoltaic properties by a simple adjustment of alkyl and π-bridge lengths. Modification of the well-known triphenylamine (TPA) core in the star-shaped oligomers by methoxy groups increases not only solubility, but also crystallinity of the oligomers, whereas their photovoltaic performance stays on a similar level as their analogs with a TPA core. The study demonstrates that these design strategies represent interesting and simple tools for the effective modulation of properties of star-shaped molecules.

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1. Introduction

Solar cells based on organic semiconductors are developing as a promising cost-effective alternative to silicon-based solar cells due to their easy fabrication by solution processing, lightweight, and compatibility with flexible substrates.[1–3] Despite the fact that conjugated polymers are dominating the field of bulk heterojunction (BHJ) organic solar cells (OSCs),[4] small molecules are receiving increasing attention due to their well-defined molecular structures, ease of functionalization, amenability to standard organic purification and characterization methods, and reduced batch-to-batch variability. Recently, there has been significant progress in the development of small molecules for use in BHJ OSCs.[5–7] The dynamic development of solution-processed small molecule OSCs has recently led to high power conversion efficiencies (PCEs) of over 10%.[8,9] Despite that the development of cheap and stable photoactive materials as well as novel design strategies for small molecules is still key to boost their potential for commercial applications.

Oligothiophenes and their derivatives with well-defined structures possess extensive π-electron delocalization along the molecular backbone and are well known as good hole-transporting materials.[10] Despite their excellent semiconducting properties, they do not absorb strongly in the red and

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Inkjet printed silver nanowire percolation networks as electrodes for highly efficient semitransparent organic solar cells

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Highlights

- Inkjet printing of silver nanowires (AgNW) of 30 µm in length has been achieved.
- Without ultrasonic scission of the wires or silver nitrate addition.
- Non-aqueous AgNW ink formulation allows printing also on water sensitive substrates.
- High boiling point alcohol component of AgNW ink prevents nozzle clogging.
- Fully ink jet printed organic solar cells with AgNW electrodes reach PCE of 4.3%.

Abstract

In this work, we demonstrate inkjet printing of silver nanowires (AgNW) with an average length of 10's of µm using industrial printheads with nozzle diameters in the same size range. The printed silver nanowire mesh reveals uniform distribution and a good balance between conductivity and transmittance, which is comparable to layers fabricated by conventional methods like slot-die or spray coating. Employing a novel AgNW ink formulation based on a high boiling alcohol allows printing directly on PEDOT:PSS and prevents nozzle clogging. Using silver nanowire meshes as bottom and top electrodes, a fully inkjet printed semitransparent organic solar cell with a power conversion efficiency of 4.3% for 1 cm^2 area is demonstrated, which is the highest value reported so far for fully inkjet printed organic photovoltaic cells.

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Time-Dependent Morphology Evolution of Solution-Processed Small Molecule Solar Cells during Solvent Vapor Annealing

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Morphological modification using solvent vapor annealing (SVA) provides a simple and widely used fabrication option for improving the power conversion efficiencies of solution-processed bulk heterojunction (BHJ) small molecule solar cells. Previous reports on SVA have shown that this strategy influences the degree of donor/acceptor phase separation and also improves molecular donor ordering. A blend composed of a dithienopyrrole containing oligothiophene as donor (named UU07) and [6,6]-phenyl-C61-butyric acid methyl ester as acceptor is investigated with respect to SVA treatment to explore the dynamics of the BHJ evolution as a function of annealing time. A systematic study of the time dependence of morphology evolution clarifies the fundamental mechanisms behind SVA and builds the structure–property relation to the related device performance. The following two-stage mechanism is identified: Initially, as SVA time increases, donor crystallinity is improved, along with enhanced domain purity resulting in improved charge transport properties and reduced recombination losses. However, further extending SVA time results in domains that are too large and a few large donor crystallites, depleting donor component in the mixed domain. Moreover, the larger domain microstructure suffers from enhanced recombination and overall lower bulk mobility. This not only reveals the importance of precisely controlling SVA time on gaining morphological control, but also provides a path toward rational optimization of device performance.

1. Introduction

Small molecule organic solar cells (SMOSCs) have attracted extensive attention due to their well-defined molecular structures, high reproducibility, easy purification as well as low fabrication costs achievable via solution-processing methods.[1,2] The dynamic development in solution-processed SMOSCs with the most promising bulk heterojunction (BHJ) configuration has recently led to high power conversion efficiencies (PCEs) of over 9%,[3–5] primarily due to improved molecular design and enhanced morphological control. Apart from a smart molecular design, microstructure engineering is one of the key strategies to achieve well-ordered and crystalline domains,[6] allowing to further improve device performance. Generally, BHJ composites comprise a donor (D) and an acceptor (A) that are arranged in multiple phases,[6] among them a crystalline donor and aggregated acceptor phase as well as a mixed amorphous or disordered regime resulting from partial miscibility of the components.[7–9] This remarkable interpenetrating network with domain sizes on the ≈ 10 nm length scale as well as a suitable D/A interfacial area is beneficial to enhanced exciton dissociation and improved charge transport,[10] and thus yields enhanced device efficiency. Besides, a well-connected acceptor network in the amorphous mixed regions can promote effectively geminate pair splitting, and thus result in near unity internal quantum efficiency for a device.[11] However, phase separation is a complex process often resulting in metastable morphologies due to rapid solvent evaporation, unbalanced solubilities

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Fully Solution-Processed Small Molecule Semitransparent Solar Cells: Optimization of Transparent Cathode Architecture and Four Absorbing Layers

Jie Min, Carina Bronnbauer, Zhi-Guo Zhang, Chaohua Cui, Yuriy N. Luponosov, Ibrahim Ata, Peter Schweizer, Thomas Przybilla, Fei Guo, Tayebeh Ameri, Karen Forberich, Erdmann Spiecker, Peter Bäuerle, Sergei A. Ponomarenko, Yongfang Li, and Christoph J. Brabec*

Semitransparent solar cells (SSCs) can open photovoltaic applications in many commercial areas, such as power-generating windows and building integrated photovoltaics. This study successfully demonstrates solution-processed small molecule SSCs with a conventional configuration for the presently tested material systems, namely BDTT-S-TR:PC$_{70}$BM, N(Ph-2T-DCN-Et)$_3$:PC$_{70}$BM, SMPV1:PC$_{70}$BM, and UU07:PC$_{60}$BM. The top transparent cathode coated through solution processes employs a highly transparent silver nanowire as electrode together with a combination interface bilayer of zinc oxide nanoparticles (ZnO) and a perylene diimide derivative (PDINO). This ZnO/PDINO bilayer not only serves as an effective cathode buffer layer but also acts as a protective film on top of the active layer. With this integrated contribution, this study achieves a power conversion efficiency (PCE) of 3.62% for fully solution-processed SSCs based on BDTT-S-TR system. Furthermore, the other three systems with various colors exhibited the PCEs close to 3% as expected from simulations, demonstrate the practicality and versatility of this printed semitransparent device architecture for small molecule systems. This work amplifies the potential of small molecule solar cells for window integration.

1. Introduction

Organic solar cells (OSCs) are extremely attractive candidates for use in next-generation solar cell technologies with affordable, clean, and renewable energy.[1,2] Advantages of the bulk heterojunction (BHJ) OSCs include low-cost fabrication of large-area devices through solution-based manufacturing processes, light-weight, mechanical flexibility, easy tunability of the physical and chemical properties of the photovoltaic materials as well as substrate and shape freedom.[3] To reach commercialization and mass production, OSCs must not only exhibit high performance and stability of traditional solar cells,[4] but also need to show unique advances for broader applications, such as elastic solar cells and visibly transparent photovoltaic devices.[5] Recently, developing transparent or semitransparent solar cells with high

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High efficiency and stability small molecule solar cells developed by bulk microstructure fine-tuning

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ABSTRACT

Morphological control over the bulk heterojunction (BHJ) microstructure of a high-efficiency small molecule photovoltaic system composed of a quinquethiophene based molecule (DRCN5T) as electron donor and [6,6]-phenyl-C71-butyric acid methyl ester ($PC_{70}BM$) as electron acceptor is demonstrated using three different post-processing strategies, including thermal annealing (TA), solvent vapor annealing (SVA), and two-step annealing (TA-SVA) treatments. We systematically analyze the processing condition-microstructure-device property relationships, explore the corresponding morphology evolution and their effects on carrier transport and recombination dynamics in BHJs as well as understand the nature of phase-separation process resulting in light-induced degradation mechanisms. Within the investigated results, the causative relations between annealing sequence, photovoltaic parameters, morphology evolution and charge carrier dynamics are for the first time delineated. In addition, the observed trade-offs in device efficiency and stability with respect to the well-defined morphologies are highlighted. The in-depth picture of the bulk microstructure formation and its kinetic evolution as a function of the specific post-processing approaches is a valuable asset for the design of new photovoltaic materials and thin film nanoscale architectures that are more efficient and better aid future commercialization efforts.

1. Introduction

Solution-processed organic solar cells (OSCs) have received great attention in the past two decades due to their advantages, including low cost, flexibility, lightweight, and roll-to-roll processing compatibility [1–3]. Optimization of their active layers generally requires convergence of a range of materials science and engineering expertize, including organic chemistry, emerging nanoscale characterization methodologies, optical-electronic process optimization, and device physics [4]. The most implemented active layer architecture for OSCs, a bulk heterojunction (BHJ), consists of a mixture of a photoactive polymer or a small molecule (as electron donor) with a fullerene derivative or another small molecule (as electron acceptor) [5–7]. Several constraints must be managed to engineer BHJ layers with efficient charge generation, transport and extraction [8–12]. Firstly, nanoscale phase separation impact excitons on their way to reach critical donor/acceptor (D/A) interfaces [13,14]. Secondly, internal order within these phases affects charge carrier transport [15]. Finally, the formation of interpenetrating networks of donor and acceptor phases changes the way that photogenerated holes and electrons are collected at the respective electrodes [16,17]. In an ideal situation, all these structural requirements are fulfilled at the point of film formation [4]. An optimal morphology is, however, seldomly achieved during film formation due to the materials' properties and external factors [18,19]. Nevertheless, numerous strategies to improve the key metrics of BHJ OSCs by influencing the BHJ structural control during or after their solution-deposition have been explored. This includes casting solvent optimization, additives, thermal annealing (TA), solvent vapor annealing (SVA), etc [5,6,20,21]. A better understanding of the BHJ evolution employed by different processing conditions provides opportunities to establish clear structure-property relations. The latter will enable the precise control of optoelectronic properties in organic materials by targeting optimized microstructures [8,21–28].

It has been demonstrated that multiple solution processed BHJ systems benefit from post-processing strategies (e.g. TA, SVA and post-additive soaking), normally leading to morphologies, which are

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Side-Chain Engineering for Enhancing the Properties of Small Molecule Solar Cells: A Trade-off Beyond Efficiency

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Three small molecules with different substituents on bithienyl-benzo[1,2-b:4,5-b′]dithiophene (BDTT) units, BDTT-TR (*meta*-alkyl side chain), BDTT-O-TR (*meta*-alkoxy), and BDTT-S-TR (*meta*-alkylthio), are designed and synthesized for systematically elucidating their structure–property relationship in solution-processed bulk heterojunction organic solar cells. Although all three molecules show similar molecular structures, thermal properties and optical band gaps, the introduction of *meta*-alkylthio-BDTT as the central unit in the molecular backbone substantially results in a higher absorption coefficient, slightly lower highest occupied molecular orbital level and significantly more efficient and balanced charge transport property. The bridging atom in the *meta*-position to the side chain is found to impact the microstructure formation which is a subtle but decisive way: carrier recombination is suppressed due to a more balanced carrier mobility and BDTT based devices with the *meta*-alkylthio side chain (BDTT-S-TR) show a higher power conversion efficiency (PCE of 9.20%) as compared to the *meta*-alkoxy (PCE of 7.44% for BDTT-TR) and *meta*-alkyl spacer (PCE of 6.50% for BDTT-O-TR). Density functional density calculations suggest only small variations in the torsion angle of the side chains, but the nature of the side chain linkage is further found to impact the thermal as well as the photostability of corresponding devices. The aim is to provide comprehensive insight into fine-tuning the structure–property interrelationship of the BDTT material class as a function of side chain engineering.

1. Introduction

As an important source of renewable energy for a sustainable future, thin-film organic solar cells (OSCs) have received significant attention due to the advantages of light-weight, flexibility, low cost, and facile fabrication of roll-to-roll processing.[1–3] During the last two decades, solution-processed photovoltaic materials are rapidly showing improvements in power conversion efficiencies (PCEs) of over 10% in the OSCs with the most promising bulk heterojunction (BHJ) configuration,[4–7] majorly based on the efforts on material development,[8] morphology control,[9–12] interfacial modification,[13,14] and device architecture design.[15,16] The efficiency of OSCs continues to increase by designing new photovoltaic materials, which probably exceeds the threshold for the commercial application of OSC.[12,17] However, there are three key issues that have to be considered carefully for practical applications: high PCE, good processability and excellent long-term stability. Interestingly, most academic research articles focus on performance while operational stability, which is in the focus of applied and/or industrial research, is hardly reported. Nevertheless, the long-term stability of OSCs will decide its market success.

Reviewing recent OSC progress from investigating thousands of photovoltaic materials,[8,18,19] several requirements need to be satisfied simultaneously in order to guarantee good performance: excellent film formation, good solubility and miscibility in green solvents, spectrally wide and efficient absorption, matched energy levels, high charge transport properties, etc.[12,16] First structure–performance relationships and general guidelines for the molecular design of efficient OSC semiconductors were reported,[8,16] however, at the risk of providing a snapshot for a research field rapidly moving toward applications.[20–23] Additional guidelines will come from the tight limitations set by production and product development.[16,24] Such design rules were recently initiated by Bundgaard et al.[25] and contained film forming properties, the absence of post annealing or a thickness independent performance. Nevertheless, the starting point for developing such relationships always should be semiconductors

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High Performance All-Small-Molecule Solar Cells: Engineering the Nanomorphology via Processing Additives

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Abstract

The use of small volumes of solvent additive (SA) or little weights of non-volatile additives is a processing approach that has been implemented in many high/record performing bulk heterojunction (BHJ) organic solar cells (OSCs). Here, the effects of six SA systems and a di-2-thienyl-2,1,3-benzothiadiazole (DTBT) molecule additive were studied with respect to the photovoltaic parameters of solution-processed all small molecule solar cells (all-SMSCs) based on BDTT-S-TR:NIDCS-MO system. An effective strategy with binary additives has been employed in this all-SM system, where a small amount, 0.75 vol% 1,8-Diiodooctane (DIO) and 2 wt% DTBT were added to the casting solution. This efficient SA approach yielded the highest power conversion efficiency (PCE) of 5.33%. The relevant additives facilitate phase separation in the nm domains and improve bulk transport as evidenced by photoluminescence (PL), atomic force microscopy (AFM), X-ray diffraction (XRD) measurements and space charge limited current (SCLC) measurements.

Keywords: solvent additive; binary additive; all small molecule; phase separation; bulk transport

Giant Rashba Splitting in $CH_3NH_3PbBr_3$ Organic-Inorganic Perovskite

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As they combine decent mobilities with extremely long carrier lifetimes, organic-inorganic perovskites open a whole new field in optoelectronics. Measurements of their underlying electronic structure, however, are still lacking. Using angle-resolved photoelectron spectroscopy, we measure the valence band dispersion of single-crystal $CH_3NH_3PbBr_3$. The dispersion of the highest energy band is extracted applying a modified leading edge method, which accounts for the particular density of states of organic-inorganic perovskites. The surface Brillouin zone is consistent with bulk-terminated surfaces both in the low-temperature orthorhombic and the high-temperature cubic phase. In the low-temperature phase, we find a ring-shaped valence band maximum with a radius of 0.043 $Å^{-1}$, centered around a 0.16 eV deep local minimum in the dispersion of the valence band at the high-symmetry point. Intense circular dichroism is observed. This dispersion is the result of strong spin-orbit coupling. Spin-orbit coupling is also present in the room-temperature phase. The coupling strength is one of the largest ones reported so far.

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Organic-inorganic perovskite compounds (OIPCs) have potential applications in optoelectronics ranging from high-efficiency thin film solar cells [1–3] to photodetectors [4] and scintillators [5], and from optical refrigeration [6] to low-threshold nanolasers [7]. Yet, fundamental questions remain open concerning the electronic structure underlying their favorable phototransport properties. Relativistic effects, i.e., spin-orbit coupling (SOC) and the resulting spin splitting, are expected because of the constituting heavy elements [8–12]. The spin splitting could be strong enough to contribute to the long carrier lifetimes in OIPCs [13–15], and to allow for the implementation in OIPC-based spintronic devices [16,17]. However, the spin splitting found in calculations [18–20] is extremely sensitive to the orientation of the organic cation and to distortions of the inorganic cage, with calculated Rashba parameters of energetically similar structures [19] ranging from <0.1 to almost 10 eV Å. As direct measurements of the electronic structure are lacking [21], the actual extent of Rashba splitting in OIPCs remains unknown. Yet, the intense circular dichroism in pump-probe spectroscopy [22] and the spin dependence of the charge dissociation and recombination at room temperature [23] in $CH_3NH_3PbI_3$ hint to the possibility to create spin polarization in OIPCs.

We report measurements of the electronic structure of single-crystal $CH_3NH_3PbBr_3$ using angle-resolved photoelectron spectroscopy (ARPES). $CH_3NH_3PbBr_3$ grows large cubic single crystals [24,25], as shown in Fig. 1, suitable for cleaving in ultrahigh vacuum and for ARPES experiments. Applying a leading edge method that takes into account the density of states (DOS) of the OIPC, we extract the dispersion of the highest-energy valence band (VB). We find a spin splitting of the band, quantified by the Rashba parameter α. The effect of the Rashba splitting on the band dispersion is illustrated in Fig. 1. Rashba splitting arises when orbitals with SOC are subject to symmetry-breaking electric fields. It causes a splitting of a doubly spin-degenerate band into two bands shifted with respect to each other in k space by k_0. At the central high-symmetry point, a minimum arises of depth E_0. For $CH_3NH_3PbBr_3$ we find Rashba parameters $\alpha = 2E_0/k_0$ of 7 ± 1 and 11 ± 4 eV Å in the orthorhombic and the cubic phase, respectively. These values are amongst the highest ones reported [26]. Our findings point out the critical role of local inversion-symmetry breaking fields in OIPCs, and of the resulting spin splitting [18–20]. We hope our study will stimulate further investigations of spin structure in OIPCs to elucidate the role of spin splitting and possible spin polarization in existing and future applications.

Crystals were synthesized according to the modified procedure in Ref. [24]. For details of the sample preparation see Fig. S1 of the Supplemental Material [27]. The resulting $CH_3NH_3PbBr_3$ single crystals with sizes of 5 mm are shown in Fig. 1(c). They exhibit a cubic shape, exposing (001)-oriented facets. Clean surfaces were prepared by cleaving crystals in vacuum (base pressure 10^{-6} Pa) parallel to the exposed (001) face. This results in a single, optically flat terrace with an area of several square millimeters. Samples were then transferred to ultrahigh vacuum (base pressure 2×10^{-8} Pa) within 1 min. We monitor the possible loss of

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Tunable doping in PbS nanocrystal field-effect transistors using surface molecular dipoles

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We study the effect of self-assembled monolayer (SAM) treatment of the SiO_2 dielectric on the electrical characteristics of PbS transistors. Using SAMs, we observe threshold voltage shifts in the electron transport, allowing us to tune the electrical properties of the devices depending on the SAM molecule used. Moreover, the use of a specific SAM improves the charge carrier mobility in the devices by a factor of three, which is attributed to the reduced interface traps due to passivated silanol on the SiO_2 surface. These reduced traps confirm that the voltage shifts are not caused by the trap states induced by the SAMs. [http://dx.doi.org/10.1063/1.4966208]

The need for electronic devices, which can be produced at low cost and with low energy consumption, has led to an increasing attention to solution-processed materials. One of the most promising classes of these materials is colloidal nanocrystals (CNCs) due to their size-tunable band gap, simple synthesis, and easy control.[1–9] Because of their interest for solar cell fabrication and the high quality of the synthesized material, PbS NCs are one of the most intensively studied semiconductors in colloidal form. Many efforts have also been made to utilize PbS CNCs for field-effect transistors (FETs).[10–16] The FETs based on this material offer ambipolar transport,[10–12,14–17] which is prospective for light-emitting device applications.[18–20] However, their use is still challenging because of the limited charge carrier mobility determined by the high density of charge carrier traps in the active material. As interfacial devices, dangling bonds on the oxide gate dielectric further hamper the charge carrier mobility in FETs based on this material.[12] This, in turn, becomes an obstacle to understand the charge carrier transport in this material, which is essential to broaden their applicability.

Increasing carrier concentration through doping is used to improve film conductivity as well as charge carrier mobility in different types of semiconductors. This effort has been widely performed in organic FETs, whereas doping in colloidal nanocrystals is generally attempted by exploiting different ligands.[3,7,8,10,13–16,21–27] Heavy doping in lead chalcogenide nanocrystals using donor molecules, such as cobaltocene ($CoCp_2$), has also been investigated.[28] Doping with these donor molecules has enabled strong n-type transport in electronic devices. However, these heavily doped PbS

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Characterization of ZnO Interlayers for Organic Solar Cells: Correlation of Electrochemical Properties with Thin-Film Morphology and Device Performance

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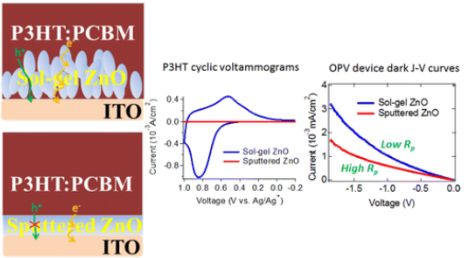
Abstract



This report focuses on the evaluation of the electrochemical properties of both solution-deposited sol–gel (sg-ZnO) and sputtered (sp-ZnO) zinc oxide thin films, intended for use as electron-collecting interlayers in organic solar cells (OPVs). In the electrochemical studies (voltammetric and impedance studies), we used indium–tin oxide (ITO) over coated with either sg-ZnO or sp-ZnO interlayers, in contact with either plain electrolyte solutions, or solutions with probe redox couples. The electroactive area of exposed ITO under the ZnO interlayer was estimated by characterizing the electrochemical response of just the oxide interlayer and the charge transfer resistance from solutions with the probe redox couples. Compared to bare ITO, the effective electroactive area of ITO under sg-ZnO films was ca. 70%, 10%, and 0.3% for 40, 80, and 120 nm sg-ZnO films. More compact sp-ZnO films required only 30 nm thicknesses to achieve an effective electroactive ITO area of ca. 0.02%. We also examined the electrochemical responses of these same ITO/ZnO heterojunctions overcoated with device thickness pure poly(3-hexylthiophehe) (P3HT), and donor/acceptor blended active layers (P3HT:PCBM). Voltammetric oxidation/reduction of pure P3HT thin films on ZnO/ITO contacts showed that pinhole pathways exist in ZnO films that permit dark oxidation (ITO hole injection into P3HT). In P3HT:PCBM active layers, however, the electrochemical activity for P3HT oxidation is greatly attenuated, suggesting PCBM enrichment near the ZnO interface, effectively blocking P3HT interaction with the ITO contact. The shunt resistance, obtained from dark current–voltage behavior in full P3HT/PCBM OPVs, was dependent on both (i) the porosity of the sg-ZnO or sp-ZnO films (as revealed by probe molecule electrochemistry) and (ii) the apparent enrichment of PCBM at ZnO/P3HT:PCBM interfaces, both effects conveniently revealed by electrochemical characterization. We anticipate that these approaches will be applicable to a wider array of solution-processed interlayers for “printable” solar cells.

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Combined Computational Approach Based on Density Functional Theory and Artificial Neural Networks for Predicting The Solubility Parameters of Fullerenes

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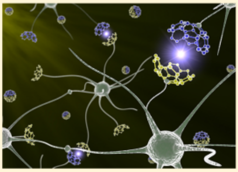
Supporting Information



ABSTRACT: The solubility of organic semiconductors in environmentally benign solvents is an important prerequisite for the widespread adoption of organic electronic appliances. Solubility can be determined by considering the cohesive forces in a liquid via Hansen solubility parameters (HSP). We report a numerical approach to determine the HSP of fullerenes using a mathematical tool based on artificial neural networks (ANN). ANN transforms the molecular surface charge density distribution (σ-profile) as determined by density functional theory (DFT) calculations within the framework of a continuum solvation model into solubility parameters. We validate our model with experimentally determined HSP of the fullerenes C_{60}, $PC_{61}BM$, bis$PC_{61}BM$, ICMA, ICBA, and $PC_{71}BM$ and through comparison with previously reported molecular dynamics calculations. Most excitingly, the ANN is able to correctly predict the dispersive contributions to the solubility parameters of the fullerenes although no explicit information on the van der Waals forces is present in the σ-profile. The presented theoretical DFT calculation in combination with the ANN mathematical tool can be easily extended to other π-conjugated, electronic material classes and offers a fast and reliable toolbox for future pathways that may include the design of green ink formulations for solution-processed optoelectronic devices.

INTRODUCTION

The imminent impact of climatic change as well as the world's growing demand for energy requires fostering new forms of sustainable energy conversion involving low-waste and low-energy manufacturing. Because solution processing can facilitate large scale industrial deployment at reduced energy consumption, accurate theoretical predictions of the thermodynamic, transport, chemical reactions, and electronic structure properties of solutes in solvents can effectively advance sustainable technologies. In this context, organic semiconductors bear a pivotal role because, as opposed to most traditional inorganic semiconductors, these material systems provide access to optoelectronic devices with tailored semiconductor properties, innovative form factors, low specific weight, and color tunability at potentially very low cost.[1] To realize these advantages, high solubility, ideally in environmental benign "green" solvents, has to be ensured.[2] This calls for a calculation approach of the cohesive forces of organic semiconductors in solution and makes the ability to predict solubility parameters very desirable. Importantly, the solubility of organic semiconductors not only affects the processability but may have important implications on the electronic performance of a finished device. For instance, the solubility of organic semiconductors may determine the sensitive morphology of both neat semiconductors and bulk heterojunction blends, particularly when considering the drying process of printed films.[3,4]

The solubility, and equally important, the electronic and morphological compatibility, of fullerenes with a plethora of p-type semiconductors makes fullerenes widely suited n-type semiconductors for organic and hybrid electronic devices. Conversely, the molecular structure properties, such as the rigidness and well-defined spheroid-like geometry, combined with relatively low-lying LUMO energy levels and resulting efficient three-dimensional electron transport in pristine as well as blended composites, are unique attributes, which render

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The influence of CPC reflectors on the electrical incidence angle modifier of c-Si cells in a PVT hybrid collector

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Abstract

PVT collectors aim for the co-generation of pv electricity and heat. The following concept intents to raise the thermal efficiency by concentrating sunlight with CPC reflectors, in order to access a higher number of solar thermal applications.

The work presented here, focuses on the influence of the CPC reflectors on the pv efficiency. Parabolic concentrators in general, and CPC reflectors in particular, cause a non-uniform illumination of the pv cells, which decreases the pv efficiency. Ray tracing calculations of one particular CPC geometry result in a characteristic, angular dependent solar flux distribution in the cell plane.

The effect of this flux distribution was measured on a real scale experimental collector on a outdoor solar test stand. The incidence angle modifier (IAM) of the pv efficiency was measured for three different concentrations, as well as for an improved CPC geometry, aiming to homogenize the flux distribution in the cell plane.

The experiments showed, that the pv efficiency drops from 15% at STC to between 9% and 11%, depending on the solar concentration factor, which influences the efficiency negatively. The predicted efficiency boost of the improved CPC geometry could not be validated experimentally, as the additional optical losses of the more complex setup were high compared to its improvement effect.

In order to understand these results, a theoretical model was built, combining ray tracing, electrical and thermal modeling of the CPC PVT collector. This model enabled to calculate the temperature distribution, as well as the pv efficiency simultaneously, by dividing the pvt absorber into finite elements.

Keywords: CPC; PVT; Hybrid; Fluid; Concentrating; Flux distribution

1. Introduction

1.1. The CPC PVT collector concept

The presented results are part of a research project, developing a stationary low concentrating PVT flat collector with front side glazing (Fig. 1). The objective is the co-generation of electricity and heat on a medium temperature level of 40–120 °C. For the concentration of sunlight, CPC

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Increased thermal stabilization of polymer photovoltaic cells with oligomeric PCBM†

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The first oligomerisation of phenyl-C_{61}-butyric acid methyl ester (PCBM) using a facile atom transfer radical addition polymerization (ATRAP) and its exploitation for organic photovoltaic devices is described. Oligo{(phenyl-C_{61}-butyric acid methyl ester)-*alt*-[1,4-bis(bromomethyl)-2,5-bis(octyloxy)benzene]} (OPCBMMB) shows opto-electronic properties equivalent to those of PCBM but has a higher glass transition temperature. When mixed with various band gap semiconducting polymers, OPCBMMB delivers performances similar to PCBM but with an enhanced stabilization of the bulk heterojunction in photovoltaic devices on plastic substrates under thermal stress, regardless of the degree of crystallinity of the polymer and without changing opto-electronic properties.

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Introduction

Phenyl-C_{61}-butyric acid methyl ester (PCBM) is a ubiquitous material in organic photovoltaics due to its high electron affinities and mobilities.[1–3] As the electron acceptor of choice in photoactive layers in bulk heterojunction (BHJ) devices, it has dominated research studies for the last decade or so in combination with poly(3-hexylthiophene).[4] More recently it has clearly demonstrated its aptness for use with a wide range of low band gap electron donor polymers,[5,6] small molecules,[7] and has even found employment in perovskite solar cells as an electron extraction layer,[8] confirming its exceptional position in device manufacturing and research. Specific to BHJs is its nano-scale morphology,[9] with a tendency to organise in amorphous and crystalline domains,[10] ideally within the exciton diffusion length, and with a beneficial vertical distribution that facilitates charge percolation.[11] However, the morphology of PCBM blends is not stable in BHJs. Fullerenes tend to diffuse through layers to form large μm-scale crystals or to accumulate at active layer-electrode interfaces,[12] both occurring notably when heated above the glass transition temperature and potentially leading to reductions in device efficiencies.[11,13,14] While photo-induced reactions between PCBM molecules may lead to morphological stability,[15,16] they can also give rise to dimers that act as charge traps and reduce short circuit current (J_{sc}) values.[17] PCBM is also difficult to cast as a thin film, resulting in rough surfaces of large aggregates.

In some cases, it has been established that the addition of small amounts of nucleating agents may lead to controlled fullerene crystal growth and thus hinder coarsening of the morphology.[18] This works well in very amorphous, nucleation-limited polymer donor blends but is less effective in systems that *per se* have a high degree of fractional crystallinity.[19] PCBM oligomers could be an alternative route, as the molecules would no longer be able to easily diffuse through the device layer stack, and should form stable thin films. Ideally, the oligomer should retain the opto-electronic properties of the PCBM molecule. In the past, fullerene (C_{60}) and PCBM were incorporated into macromolecules as pendent moieties.[20] While this remains one route, it can let the fullerene sphere continue to form aggregates,[21] possibly because of the high degrees of freedom. Nevertheless, pendent fullerenes

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† Electronic supplementary information (ESI) available: Equipment details, XPS results, TGA and DSC thermograms, AM1 level calculations and data, UV solid state spectra, and organic photovoltaic device data. See DOI: 10.1039/c6tc03290g

Coloring Semitransparent Perovskite Solar Cells *via* Dielectric Mirrors

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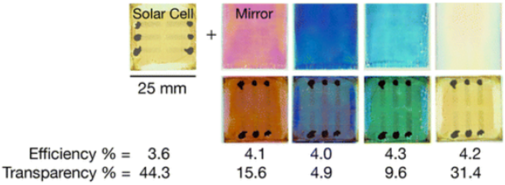
Abstract



While perovskite-based semitransparent solar cells for window applications show competitive levels of transparency and efficiency compared to organic photovoltaics, the color perception of the perovskite films is highly restricted because band gap engineering results in losses in power conversion efficiencies. To overcome the limitation in visual aesthetics, we combined semitransparent perovskite solar cells with dielectric mirrors. This approach enables one to tailor the device appearance to almost any desired color and simultaneously offers additional light harvesting for the solar cell. In the present work, opto-electrical effects are investigated through quantum efficiency and UV-to-visible spectroscopic measurements. Likewise, a detailed chromaticity analysis, featuring the transmissive and reflective color perception of the device including the mirror, from both sides and in different illumination conditions, is presented and analyzed. Photocurrent density enhancement of up to 21% along with overall device transparency values of up to 31% (4.2% efficiency) is demonstrated for cells showing a colored aesthetic appeal. Finally, a series of simulations emulating the device chromaticity, transparency, and increased photocurrent density as a function of the photoactive layer thickness and the design wavelength of the dielectric mirror are presented. Our simulations and their experimental validation enabled us to establish the design rules that consider the color efficiency/transparency interplay for real applications.

Keywords:
Bragg mirror; dielectric mirror; perovskite photovoltaics; room temperature crystallization; semitransparent;

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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 mobilities. 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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Polymer-based scattering layers for internal light extraction from organic light emitting diodes

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ABSTRACT

Efficient light extraction for organic light emitting diodes (OLED) using scalable processes and low-cost materials are important prerequisites for the future commercialization of OLED lighting devices. The light-extraction technology exhibited in this paper uses polymer-based high-refractive index scattering layers processed from solution. The scatter matrix formulation incorporates two types of nanoparticles for refractive index tuning and scattering, respectively. Planarization by the same material in order to reduce surface defects was critical for achieving highly increased device yield. Highly efficient and defect-free large-area (1.8 cm^2) white OLED devices were fabricated on top of the scattering layer in a bottom emitter configuration. Light extraction enhancement leads to an overall efficiency gain of up to 81% for luminances of 5000 cd m^{-2}.

1. Introduction

Today, organic light-emitting diodes (OLEDs) are a promising technology for the future of illumination. OLED's unique features like transparency, flexibility and thinness offer new possibilities for design and application. However, to be competitive with conventional light sources, the price per lumen needs to be reduced [1]. Increasing light extraction is an appropriate approach to increase the performance of the device [2]. However, the additional cost of light extraction measures should be kept to a minimum. Many schemes for increasing the light extraction in OLEDs have been proposed [3]. In this work, we present an outcoupling technology for internal light extraction which combines the benefits of low-cost materials, scalable processes, and high efficiency gain.

Due to the different refractive indices of the substrate ($n \sim 1.5$) and the organic layers ($n \sim 1.8$) – where light emission takes place – light is trapped by total internal reflection. The organic layers are sandwiched between a reflective metallic cathode and a transparent anode (indium tin oxide - ITO). Around 30% is trapped in the glass substrate and ~50% in the high refractive index region of the ITO/organic layers [4]. Hence, only ~20% of the generated light can escape the device. The angular range in that the escaping light propagates is called the escape cone. By adding a light extraction layer, the trapped light can be redistributed, so that some of it also reaches the escape cone.

The light trapped in the substrate can be accessed using external extraction on the side of the substrate that faces air. Common techniques are micro lens arrays or scattering layers attached to the substrate after processing the OLED devices on the opposite site of the substrate [5,6] The substrate modes and the ITO/organic-modes can be redistributed by introducing internal light extraction layers (IEL), which results in enhanced light out-coupling [3,7,8]. To access the light trapped inside the organic layers, the refractive index of the IEL layers needs to be equal to or higher than that of the ITO/organic layers. Equally important for the efficiency gain induced by the internal light extraction layer are the layer's other optical properties such as haze and absorption. The lower the absorption of the IEL, the higher the overall efficiency.

Light scattering, micro lenses or photonic structures can be used for internal light recycling [3]. Some of those techniques are either very expensive or cannot be applied to large areas or high volume

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SCIENTIFIC REPORTS

Nanoscale Morphology of PTB7 Based Organic Photovoltaics as a Function of Fullerene Size

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High efficiency polymer:fullerene photovoltaic device layers self-assemble with hierarchical features from ångströms to 100's of nanometers. The feature size, shape, composition, orientation, and order all contribute to device efficiency and are simultaneously difficult to study due to poor contrast between carbon based materials. This study seeks to increase device efficiency and simplify morphology measurements by replacing the typical fullerene acceptor with endohedral fullerene $Lu_3N@PC_{80}BEH$. The metal atoms give excellent scattering contrast for electron beam and x-ray experiments. Additionally, $Lu_3N@PC_{80}BEH$ has a lower electron affinity than standard fullerenes, which can raise the open circuit voltage of photovoltaic devices. Electron microscopy techniques are used to produce a detailed account of morphology evolution in mixtures of $Lu_3N@PC_{80}BEH$ with the record breaking donor polymer, PTB7 and coated using solvent mixtures. We demonstrate that common solvent additives like 1,8-diiodooctane or chloronapthalene do not improve the morphology of endohedral fullerene devices as expected. The poor device performance is attributed to the lack of mutual miscibility between this particular polymer:fullerene combination and to co-crystallization of $Lu_3N@PC_{80}BEH$ with 1,8-diiodooctane. This negative result explains why solvent additives mixtures are not necessarily a morphology cure-all.

Organic photovoltaics (OPV) have been intensely studied over the past two decades and have steadily made progress increasing the device efficiency. The breakthrough of the 10% efficiency mark has been achieved with both single and multi-junction cells[1–8]. Improved understanding of the local ordering and morphology of the component materials has been a large contributor to this steady improvement[9–14].

A commonly studied high performing a polymer device is composed of 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 phenyl-C71-butric acid methyl-ester ($PC_{70}BM$) with a processing additive diiodooctane (DIO) used for improved morphology and performance[15–18]. The DIO additive improves the power conversion efficiency (PCE) by at least a factor of two. The widely accepted reason for the improved performance is that the DIO decreases the component domain sizes from solution coating, thereby increasing interfacial area, exciton dissociation and the associated photocurrent[19–22]. DIO and other low volatility solvent additives have been widely reported in the OPV literature to decrease the polymer fullerene domain size by preventing liquid-liquid phase separation[14]. Reports on solvent mixtures always and without fail record an improvement in device function by use of a solvent additive. Due to the selection of positive results for published articles there are therefore no reports in which the use of a solvent additive results in poorer performance nor any analysis for why a solvent additive could result in a less advantageous morphology.

The nanoscale morphology of organic mixtures is very difficult to study due to lack of contrast between organic materials. Non-imaging techniques such as x-ray diffraction, neutron scattering, or various spectroscopies are typically used to infer average geometries and mixing ratios. Electron microscopy techniques are gaining popularity, but 2D images provide vertically averaged data. Tomography techniques can provide a 3D

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Chemical stability of carbon-based inorganic materials for *in situ* x-ray investigations of ammonothermal crystal growth of nitrides

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ABSTRACT

The chemical stability of diamond, silicon carbide, vitreous carbon, and boron carbide in supercritical ammonia containing different mineralizers was investigated. The materials were found to show good corrosion resistance in the presence of selective or all tested mineralizers.

Diamond was found to be virtually inert in both ammonoacidic and ammonobasic reaction media.

Silicon carbide showed good chemical stability in varying ammonothermal reaction media.

The chemical stability of vitreous carbon was found to depend on its manufacturing temperature.

Corrosion of boron carbide strongly depends on the mineralizer used as well as on applied mechanical stress.

Based on their chemical stability and mechanical properties, the applicability of the materials in the respective ammonothermal reaction media as construction materials is evaluated. Additionally, the applicability of the materials as a window material for both high energy *in situ* x-ray imaging and low energy *in situ* x-ray diffraction is discussed.

1. Introduction

Ammonothermal synthesis is a promising technological approach for the growth of nitrides such as GaN [1,2] in excellent crystalline quality [3–5] as well as for the synthesis of novel nitrides and related materials [1,6]. In ammonothermal crystal growth research, direct insight into ammonothermal high-pressure autoclaves is very desirable but rarely available due to the challenging process conditions such as high pressure and high temperature. In addition, supercritical ammonia containing mineralizers is a reaction medium that is very corrosive to most suitable construction materials [7]. Recently, sapphire has been applied successfully as a window material for *in situ* x-ray imaging of nitrides under ammonothermal conditions using high energy x-rays [8]. The chemical stability of some ceramic materials has previously been investigated, including their applicability as liner material (in combination with sapphire windows) in high energy *in situ* x-ray imaging [9]. However, penetrating these ceramics (*e.g.* Si_3N_4) with x-rays requires rather high photon energy (*e.g.* 100 keV). In order to extend the possibilities of *in situ* x-ray measurements towards studies of the evolution of crystal quality during growth, applying lower energy x-rays (using *e.g.* Mo or Ag anode, about 20 keV) is necessary for achieving high angular resolution in diffraction experiments. Thus, a window material with lower absorption for low energy x-rays is required.

In this work, we investigate the chemical stability of materials with low x-ray absorption that enable high resolution *in situ* x-ray diffraction using low photon energy. Carbon-based inorganic materials are promising candidates as they may combine good chemical stability under ammonothermal conditions with good mechanical stability as well as low x-ray absorption. Therefore, the chemical stability of diamond, silicon carbide, vitreous carbon, and boron carbide in ammonothermal reaction media are evaluated and the applicability of the investigated materials in the respective ammonothermal reaction media is discussed.

2. Materials and methods

2.1. Selection of investigated materials

For the application as a construction material in high pressure

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Determination of the Molar Extinction Coefficient of Colloidal Selenium for Optical Characterization of Stabilized Nanoparticulate Dispersions

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Abstract

To prepare fully printed copper-indium-diselenide solar-cell-absorbers it is necessary to have well defined and printable precursor-inks. In this work, the synthesis and different approaches for the colloidal stabilization of Selenium (Se) nanoparticles are presented, which should ultimately serve as a selenium source for CISe absorbers. The produced particles were stabilized with different concentrations of Polyvinylpyrrolidone (PVP) and micelles (TX100) respectively. The resulting suspensions were analyzed in aspect of particle size and colloidal stability using dynamic light scattering (DLS). It was shown, that both approaches lead to stable colloidal suspensions with ca. 80 - 100 nm particle size. The PVP stabilized suspension stays stable for four weeks at a Zeta potential of > 35 - 25 mV whereas the TX100 stabilized suspension was only short-time-stable due to loss in Zeta potential over time. UV/VIS spectroscopy and Lambert-Beer's law were used to determine the concentration of Se in the dispersion. The molar extinction coefficient ε of colloidal selenium was calculated to be 1.44×10^3 l/(mol·cm) for ε (Se) respectively 2.63×10^7 l/(mol·cm) for ε (Se-NP) ± 9 % in both cases.

Keywords

Printable nanoparticles, Colloidal selenium, Stabilization, Dynamic light scattering, Concentration, Molar extinction coefficient, UV/VIS

Highlights

- Evaluation of PVP vs. TX100 micelles as particle stabilizer
- Determination of Se concentration in dispersion via UV/VIS spectroscopy
- Determination of molar extinction coefficient of colloidal Selenium

Introduction

$CuInSe_2$ (CISe) materials have become very attractive as absorber layer for thin film solar cells, due to a suitable band gap, a high extinction coefficient and good materials stability [1-5]. Different approaches to produce CISe via co-evaporation, pulsed Laser deposition or sputtering have been reported [6-8]. Due to process complexity and the problem of scaling up the process various non-vacuum approaches have been suggested: the Selenium integrated by annealing a Cu-In-precursor under H_2Se and N_2 atmosphere at a temperature of ~ 450°C [9]. This procedure holds highly toxic H_2Se and is potentially explosive, due to free hydrogen. Therefore the preparation of a solid Se film via sputtering, electrochemical deposition or evaporation has been considered [10-14]. So far, these approaches lead to a poor intermixture of Se and Cu-In [15]. Recent research was conducted on all-printable precursors using bimetallic Cu-In nanoparticles [16]. Such precursors may be mixed and subsequently printed, leading to a well distributed (Cu+In):Se ratio. A method to precisely monitor and tune the molar composition of the dispersion and in particular the Se content would be beneficial.

In the present work the optical transmission of Se dispersions in combination with Lambert-Beer's law is used to determine the concentration of Se in the dispersions. To apply the Lambert-Beer's law accurately, knowledge about the molar extinction coefficient is necessary. However, hardly any data are available in literature for nanoparticulate Se dispersions. To determine the molar extinction coefficient of colloidal Se we have prepared a series of Cu-In + Se dispersions with varying Se concentrations. To determine the (Cu+In):Se ratio, layers were deposited and characterized using energy dispersive X-ray spectroscopy (EDX). In parallel optical transmission/extinction of the Se dispersion was determined by UV/VIS spectroscopy. Using Lambert-Beer's law the molar extinction coefficient was deduced from the experimentally determined Se concentration and optical absorbance.

A commonly used synthesis route of Se nanoparticles is to

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Optimization of Solution-Processed Luminescent Down-Shifting Layers for Photovoltaics by Customizing Organic Dye Based Thick Films

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We theoretically and experimentally determined the optimized film properties of luminescent down-shifting (LDS) layers for thin film solar cells. Based on the predictions from an adapted optical model, we coated thick (300–500 μm) and efficient luminescent down-shifting layers from environmentally friendly solvents and industrially scalable inks. LDS layers consisted of polyvinyl butyral (PVB) as binder and organic luminescent dyes as UV-converters. The luminescence quantum yields of the dyes were studied in solution (benzyl alcohol) and for solid thick films. Our data shows that the studied dyes retain luminescent efficiencies of approximately 90 % in the solid state when processed from solution. We further apply the produced layers onto copper indium gallium diselenide (CIGS) solar cells to verify the theoretical predictions for enhancing the external quantum efficiency (EQE) in the UV region. For the best converters a remarkable enhancement of the EQE from 9 % to 52 % was recorded at 380 nm. These findings underline that printed LDS layers indeed have the potential to enhance the efficiency and the light harvesting capabilities of industrially relevant photovoltaic modules.

Introduction

Luminescent down-shifting (LDS) is an approach for improving the spectral response of solar cells in the UV and near-UV spectral regions.[1] This is usually done by applying a layer with UV-absorbing photoluminescent materials on top of a device. The layer modifies the incident solar spectrum by converting UV photons into visible light. Due to parasitic optical losses or optical filters in the UV region, most solar cell technologies have a significantly higher external quantum efficiency in the visible light region.[1] This opens the opportunity for LDS layers to enhance charge carrier generation by efficiently utilizing the otherwise lost UV photons.[2]

This approach has been successfully demonstrated on various photovoltaic technologies, including multi-crystalline Si (mc-Si),[3] copper indium gallium diselenide (CIGS),[4] cadmium telluride (CdTe)[5] solar cells, and many others.[6]

Several photoluminescent material classes have been used to this end:[7] quantum dots,[8] nanophosphors,[9] phosphors,[4b,6b] and even phosphor single crystals[10]—all showed attractive results when used for LDS. However, high costs for some material systems,[5b] environmental and health considerations, light-scattering-induced losses,[4b,11] or parasitic optical losses have so far prevented their implementation in the photovoltaic industry. Today's most commonly used materials for LDS are commercial organic luminescent molecules,[3a,c,5c] as they combine a high photoluminescence quantum yield (PLQY) close to unity[12] together with very attractive and easy processing.

To retain their luminescent properties over a long period of time, however, luminescent molecules must be embedded into a binder material.[1] Such LDS layers can potentially substitute the encapsulation layer of solar modules,[13] provided that they have the same protective properties and are transparent to visible light. Ethylene vinyl acetate (EVA) is a common encapsulation film material for silicon solar modules. Klampaftis et al. extruded EVA films with Lumogen (BASF) organic dyes for a successful demonstration of an LDS effect in several solar cell types.[3b,4a,5f] However, EVA with high enough vinyl acetate content (28–32 %) can only be solution processed from aromatic solvents, such as tolu-

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Organic and perovskite solar modules innovated by adhesive top electrode and depth-resolved laser patterning†

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We demonstrate an innovative solution-processing fabrication route for organic and perovskite solar modules *via* depth-selective laser patterning of an adhesive top electrode. This yields unprecedented power conversion efficiencies of up to 5.3% and 9.8%, respectively. We employ a PEDOT:PSS–Ag nanowire composite electrode and depth-resolved post-patterning through beforehand laminated devices using ultra-fast laser scribing. This process affords low-loss interconnects of consecutive solar cells while overcoming typical alignment constraints. Our strategy informs a highly simplified and universal approach for solar module fabrication that could be extended to other thin-film photovoltaic technologies.

Broader context

Thin-film photovoltaics using high throughput solution-based printing techniques such as roll-to-roll processing are a key technology for inexpensive and sustainable light-to-energy conversion. Moreover, the use of bendable substrates promotes aesthetically attractive, mechanically amenable and highly customized devices that could advance electronic applications and furnish architectural objects. Here, we demonstrate a micrometer thick PEDOT:PSS–Ag nanowire composite electrode with desirable optical, electrical and adhesive characteristics to establish an entirely solution-processed fabrication route for organic and perovskite solar cells and modules with laminated top electrodes. We employ depth-resolved post-patterning through laminated devices using ultra-fast laser scribing for accomplishing low-loss interconnects of consecutive solar cells thereby overcoming typical alignment constraints. This approach yields geometric fill factors of over 90% and unprecedented power conversion efficiencies of up to 5.3% and 9.8% for organic and perovskite modules with laminated top contact, respectively. Our findings inform materials and engineering strategies for achieving functional devices with integrated barriers and reducing fabrication complexity in future thin-film photovoltaic production lines.

Introduction

As we move through the Information Age, the world faces important challenges resulting from energy demand growth and a rising population. 1.2 billion people or 17% of the world's global population lack access to electricity.[1] 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[2] because they can be processed from solution and deployed on a massive scale while providing excellent form factors[3–5] and competitive power conversion efficiencies.[6–9] 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,[10] innovation in affordable and reliable large-scale fabrication techniques is imperative.[11]

To fully exploit the economical and engineering advantages with which the roll-to-roll printing technology could benefit an industrial scenario for thin-film photovoltaics, fully solution-processable photoactive and electrode materials are required. Solution-processed metal electrodes are particularly difficult to realize because of often inferior optical (*e.g.*, reflectivity) and electrical properties (*e.g.*, conductivity) as compared to the more common vacuum deposited metal electrodes. Moreover, processing a metal-based electrode from solution on top of a semi-finished stack is challenging in terms of solvent compatibility, surface energy and even surface induced damage. Nevertheless, important advances have been demonstrated lately using for instance silver ink,[12] silver nanowires,[13–15] carbon allotropes[16,17] and hybrid

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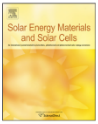

Cubic silicon carbide as a potential photovoltaic material

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ABSTRACT

In this work we present a significant advancement in cubic silicon carbide (3C-SiC) growth in terms of crystal quality and domain size, and indicate its potential use in photovoltaics. To date, the use of 3C-SiC for photovoltaics has not been considered due to the band gap of 2.3 eV being too large for conventional solar cells. Doping of 3C-SiC with boron introduces an energy level of 0.7 eV above the valence band. Such energy level may form an intermediate band (IB) in the band gap. This IB concept has been presented in the literature to act as an energy ladder that allows absorption of sub-bandgap photons to generate extra electron–hole pairs and increase the efficiency of a solar cell. The main challenge with this concept is to find a materials system that could realize such efficient photovoltaic behavior. The 3C-SiC bandgap and boron energy level fits nicely into the concept, but has not been explored for an IB behavior.

For a long time crystalline 3C-SiC has been challenging to grow due to its metastable nature. The material mainly consists of a large number of small domains if the 3C polytype is maintained. In our work a crystal growth process was realized by a new approach that is a combination of initial nucleation and step-flow growth. In the process, the domains that form initially extend laterally to make larger 3C-SiC domains, thus leading to a pronounced improvement in crystalline quality of 3C-SiC. In order to explore the feasibility of IB in 3C-SiC using boron, we have explored two routes of introducing boron impurities; ion implantation on un-doped samples and epitaxial growth on un-doped samples using pre-doped source material. The results show that 3C-SiC doped with boron is an optically active material, and thus is interesting to be further studied for IB behavior.

For the ion implanted samples the crystal quality was maintained even after high implantation doses and subsequent annealing. The same was true for the samples grown with pre-doped source material, even with a high concentration of boron impurities.

We present optical emission and absorption properties of as-grown and boron implanted 3C-SiC. The low-temperature photoluminescence spectra indicate the formation of optically active deep boron centers, which may be utilized for achieving an IB behavior at sufficiently high dopant concentrations. We also discuss the potential of boron doped 3C-SiC base material in a broader range of applications, such as in photovoltaics, biomarkers and hydrogen generation by splitting water.

1. Introduction

The solar cell market is today dominated by single junction silicon solar cells with up to 91% of the global production with respect to power output. The single junction entails that the cell can only convert a fraction of the solar spectrum into electrical

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Photoinduced degradation of methylammonium lead triiodide perovskite semiconductors†

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Photoinduced degradation is a critical obstacle for the real application of novel semiconductors for photovoltaic applications. In this paper, the photoinduced degradation of $CH_3NH_3PbI_3$ in a vacuum and air (relative humidity 40%) is analyzed by *ex situ* and advanced *in situ* technologies. Without light illumination, $CH_3NH_3PbI_3$ films slowly degrade under vacuum and air within 24 hours. However, we find that $CH_3NH_3PbI_3$ converts to metallic lead (Pb^0) when exposed to vacuum and light illumination. Further, a series of lead salts (*e.g.* PbO, $Pb(OH)_2$ and $PbCO_3$) are formed when $CH_3NH_3PbI_3$ is degraded under environmental conditions, *i.e.* under the combination of light, oxygen and moisture. Photoinduced degradation is found to be determined by the environmental atmosphere as $CH_3NH_3PbI_3$ films remain very stable under nitrogen conditions. The results from vacuum conditions underpin that the high volatility of the organic component (CH_3NH_3I) is in conflict with reaching excellent intrinsic stability due to its role in creating ion vacancies. The degradation in air suggests that both oxygen and water contribute to the fast photodecomposition of $CH_3NH_3PbI_3$ into lead salts rather than water alone. Given these basic yet fundamental understandings, the design of hydrophobic capping layers becomes one prerequisite towards long-term stable perovskite-based devices.

Introduction

Perovskite semiconductors, most notably methylammonium lead triiodide ($CH_3NH_3PbI_3$), have manifested themselves as a class of photovoltaic materials offering promising performance in light-energy conversion applications.[1] Although great success has been achieved by using $CH_3NH_3PbI_3$ as active layers to fabricate solar cells,[2] X-ray detectors,[3] light-emitting diodes (LEDs)[4] and lasers,[5] its long-term stability remains challenging.[6,7] Efforts to address this problem have already shown critical progress, and perovskite-type solar cells could maintain high power conversion efficiency extending for thousands of hours when well packaged.[8] Despite this progress, the environmental instability of the $CH_3NH_3PbI_3$ semiconductor still remains a major obstacle. A better understanding of the degradation mechanism is therefore critical to further guide the development of perovskite-based devices which are suitable for future commercialization.

The stability of $CH_3NH_3PbI_3$ has been systematically investigated and several factors, like humidity,[9] heat,[10] electric bias,[11] *etc.*, were identified as the possible reasons for degradation. For instance, the degradation of $CH_3NH_3PbI_3$ was monitored as a function of humidity, and the degradation rate was found to be strongly dependent on humidity.[9] Heat is another factor affecting stability due to the highly volatile nature and thermal instability of CH_3NH_3I.[10] In addition, by applying an electric field to $CH_3NH_3PbI_3$, organic cations ($CH_3NH_3^+$) can drift and form unstable PbI_6^{4-} octahedral complexes which further decompose into PbI_2 and excess iodide.[11]

With regard to photovoltaic materials, the relevant light stability is a crucial criterion determining the quality of the package against water and oxygen. Although the transformation of $CH_3NH_3PbI_3$ films into PbI_2 and other reaction products has been reported as mentioned above, understanding the mechanism of photoinduced degradation of $CH_3NH_3PbI_3$ is still in its infancy. Furthermore, precise knowledge of the influence of the atmosphere on the photoinduced degradation may trigger the

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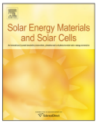

Photodegradation of Si-PCPDTBT:PCBM active layer for organic solar cells applications: A surface and bulk investigation

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Photooxidation profile

ABSTRACT

The photooxidation of a polymer blend film used in efficient solar cells based on poly[(4,40-bis(2-ethylhexyl)dithieno[3,2-b:20,30- d]silole)-2,6-diylalt-(2,1,3-benzothiadiazole)-4,7-diyl], (Si-PCPDTBT) and [6,6]-phenyl-C71-butyric acid methyl (PC70BM) has been investigated. A set of experiments from complementary techniques was developed to monitor the modifications during ageing that occur not only in the bulk but also at the surface. The surface analyses were performed by X-ray photoelectron spectroscopy (XPS) and atomic force microscopy (AFM), and the bulk analyses by UV–visible spectroscopy and infrared (IR) spectroscopy. The results reveal that the silicon bridge atom is the first target of degradation. We have identified the existence of a photooxidation profile within the 300 nm thick film. Such a heterogeneous degradation was confirmed by time-of-flight secondary ion mass spectrometry (TOF-SIMS) depth profiling.

1. Introduction

Organic photovoltaic (OPV) is a promising and complementary technology to classical PV, due to its convenient integration into the urban environment [1]. New properties such as transparency, low weight and flexibility give to the OPV devices a large adaptability.

Recently, a new low band gap conjugated polymer, poly[(4,40-bis(2-ethylhexyl)dithieno[3,2-b:20,30-*d*]silole) – 2,6-diylalt-(2,1,3-benzothiadiazole)-4,7-diyl] (Si-PCPDTBT) has been proposed for making efficient organic solar cells (OSCs) devices. [2–7] This polymer was compared to the poly[2,6-(4,4-bis-(2-ethylhexyl)-4H-cyclopenta[2,1-b;3,4-b0]dithiophene)-alt-4,7-(2,1,3-benzothiadiazole)], the C-PCPDTBT version. By changing the bridging atom from C to Si, significant improvements of the device performance have been observed. The Si-polymer is a more crystalline material than the C version which is suitable for better charge transport when blended with a fullerene derivative [6]. Additionally, the introduction of the Si atom induces a larger and more well-defined phase separation between the polymer and the fullerene which improves the charge generation and decreases the charge recombination [3]. Therefore, the performances obtained with the Si-PCPDTBT active layer are better than in the case of the carbon analogue, either with or without additive processing [8].

However, raising performances is of no use for the commercialization of the OPV technology if the stability is not maintained or increased in parallel. Depending on the OSCs application, the active layer is submitted to various sources of degradation such as light, oxygen, water and mechanical stress. While oxygen and water exposure can be reduced by packaging the devices with barrier materials, it is impossible to completely avoid oxygen diffusion during the envisaged life time of twenty years, especially when the encapsulation is supposed to be flexible and low cost. Therefore, resistant organic materials and a better understanding of the photooxidation mechanism are required. The photodegradation of various conjugated polymers or blends have been reported in the literature [9–17].

In the present work, we have investigated the photochemical

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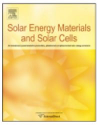

Nanostructured organosilicon luminophores in highly efficient luminescent down-shifting layers for thin film photovoltaics

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ABSTRACT

We use a new type of solution processed luminescent molecules – nanostructured organosilicon luminophores (NOLs) – in printed luminescent down-shifting layers for photovoltaic light harvesting. We show that NOLs exhibit a high luminescent efficiency of 82–90% when added into two chemically different polymer matrices that are commonly used for photovoltaic encapsulation: polyvinyl butyral and ethylene-vinyl acetate. The coated layers are optimized to maximize both UV absorbance and visible light emission and transmittance. Attaching the luminescent layers onto a CIGS solar cell significantly improves the external quantum efficiency in the UV region: from 1% to 55% at 360 nm. As a result, the short circuit current density and power conversion efficiency increase by up to 3.2–4.3%. After experimental verification of our optical simulation model, we employ it to determine the ideal molecular structure of NOLs for luminescent down-shifting applied to CIGS.

1. Introduction

Single junction solar cells have a maximum theoretical efficiency of 31% [1]. One reason for this low efficiency is lattice thermalization losses in the UV [1]. UV and near-UV photons have energies higher than the band gaps of the semiconductors used in photovoltaics, and so when these photons are absorbed, the excess energy is lost via thermalization. In addition, high energy photons are lost due to front surface recombination and parasitic absorption. Luminescent down-shifting (LDS) layers solve these problems by absorbing UV light and emitting visible light that solar cells can use more efficiently [2]. Thus when applied on top of a solar cell, LDS layers tailor the incident spectrum for more efficient current generation, and in doing so improve solar cell efficiency.

LDS layers have been successfully applied to silicon [1,3–5], CdTe [6–8], CIGS [9–11], dye-sensitized solar cells [12,13], and various other types of photovoltaic technologies. CIGS (copper–indium–gallium–(di)selenide) solar cells are of particular interest here because they perform well in visible wavelengths, but have poor efficiency in UV due to parasitic absorption in the cadmium sulfide buffer layer [9]. Applying LDS layers can be an inexpensive, purely optical means of increasing the efficiency of CIGS and other types of thin film photovoltaics.

Three classes of luminescent materials have been used for LDS: organic dyes, quantum dots, and rare earth-doped inorganic particles (phosphors) [2,14]. Organic dyes are a popular material, as they exhibit photoluminescence quantum yields (PLQY) of ~90–99%, high absorptivities, and are easily embedded in polymer matrices [2,15,16]. However, these properties come at the cost of narrow absorption bands and uncertain UV stability [2,15,17]. Quantum dots (QDs) have been investigated as an alternative

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Progress in PHOTOVOLTAICS

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RESEARCH ARTICLE

Visualizing the performance loss of solar cells by IR thermography — an evaluation study on CIGS with artificially induced defects

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ABSTRACT

Local electric defects may result in considerable performance losses in solar cells. Infrared (IR) thermography is one important tool to detect these defects on photovoltaic modules. Qualitative interpretation of IR images has been carried out successfully, but quantitative interpretation has been hampered by the lack of "calibration" defects. The aims of this study are to (i) establish methods to induce well-defined electric defects in thin-film solar cells serving as "calibration" defects and to (ii) assess the accuracy of IR imaging methods by using these artificially induced defects. This approach paves the way for improving quality control methods based on imaging in photovoltaic. We created ohmic defects ("shunts") by using a focused ion beam and weak diodes ("interface shunts") by applying a femto-second laser at rather low power on copper indium gallium selenide cells. The defects can be induced precisely and reproducibly, and the severity of the defects on the electrical performance can be well adjusted by focused ion beam/laser parameters. The successive assessment of the IR measurement (ILIT-Voc) revealed that this method can predict the losses in P_{mpp} (maximal power extractable) with a mean error of below 10%. Copyright © 2016 John Wiley & Sons, Ltd.

KEYWORDS
perfomance; imaging; PV modules; defects

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1. INTRODUCTION

Photovoltaic electric current generation is one of the most important keys for future renewable energy supply. The concept of thin-film solar cells based on copper indium gallium selenide (CIGS) is one promising approach for a further decrease of the price of PV modules. Indeed, significant progress has been achieved in increasing the efficiency up to 21.7% for single cells [1]. The power conversion efficiencies of CIGS modules have reached 18.7% for mini-modules and surpassed 15% for conventional modules easily [2]. One contribution to this discrepancy between cell and module efficiency probably results from laterally spread electric defects that may hinder a further increase in module efficiency. These defects may be either induced during processing or also during outdoor usage.

Different types of defects have been observed and result in a reduction of the module performance [3–8]. From the electrical viewpoint, defects (or shunts) may lead to a local short current. Such defects are classified depending on their electrical behavior as either weak diodes or "classic" shunts (locally reduced parallel resistance). Computer simulations have been applied modeling the electrical network of photovoltaic (PV) modules in order to understand the

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Automatized segmentation of photovoltaic modules in IR-images with extreme noise

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Highlights

- Specialized IR-images (DLIT) of solar modules suffer from low contrast.
- Development of a fast and robust algorithm for automatized module segmentation.
- Automatized segmentation is successful even under extreme noise.
- Algorithm was successfully tested on 10 samples (DLIT-images).
- The approach offers the starting ground for automatized analysis of solar modules.

Abstract

Local electric defects may result in considerable performance losses in solar cells. Infrared thermography is an essential tool to detect these defects on photovoltaic modules. Accordingly, IR-thermography is frequently used in R&D labs of PV manufactures and, furthermore, outdoors in order to identify faulty modules in PV-power plants. Massive amount of data is acquired which needs to be analyzed. An automatized method for detecting solar modules in IR-images would enable a faster and automatized analysis of the data.However, IR-images tend to suffer from rather large noise, which makes an automatized segmentation challenging. The aim of this study was to establish a reliable segmentation algorithm for R&D labs. We propose an algorithm, which detects a solar cell or module within an IR-image with large noise. We tested the algorithm on images of 10 PV-samples characterized by highly sensitive dark lock-in thermography (DLIT). The algorithm proved to be very reliable in detecting correctly the solar module. In our study, we focused on thin film solar cells, however, a transfer of the algorithm to other cell types is straight forward

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ORIGINAL PAPER

Ultrafast screening method for assessing the photostability of thin-film solar cells

Andreas Vetter[1,2] · **Klaus Burlafinger**[1] · **Christoph J. Brabec**[1,2]

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Abstract Commercial success of optoelectronical devices such as solar cells depend strongly on lifetime next to production costs and power conversion efficiency. While a steep decrease in production costs and significant increase in efficiency have been achieved, lifetime still plays often a limiting factor, in particular, in case of highly innovative new device types. Lifetime tests measuring the stability of devices without external influences (i. p. water) generally take very long time due to the required long lifetime of optoelectronical devices. We established a novel accelerated lifetime test (ALT) setup which may increase the test speed by a factor of several hundred. We verified the setup and the applicability of our ALT measurement routine with an experiment on a well-studied innovative thin-film solar cell type (P3HT:PCBM).

Keywords ALT · Optoelectronics · Thin film · PV · Solar cell · Organic photovoltaics

1 Introduction

Innovative solar cells such as thin-film photovoltaics (PV) have already started to gain a certain impact on the market, in particular, PV based on inorganic material systems such as Copper–Indium–Gallium–Diselenide (CIGS) or Cadmium-Telluride (CdTe) [1]. Thin-film solar cells may offer various advantages over standard crystalline silicon solar cells, such as the need for less material or the rather simple processing of the modules (no need for single crystal growth). Another more recent example for thin-film solar cells with extremely high potential are solution-processed solar cells based on organic semiconductor materials. However, novel and highly potential material systems generally tend to have rather low stability and degrade at considerably faster rate compared to well-established silicon PV or CIGS/CdTe.

Enabling increased lifetime of solar modules provides an essential contribution to an improvement of the “magic triangle” (Fig. 1), which describes three main influences on the profitability of installed PV [2]. Next to lifetime, this triangle consists of the factors power conversion efficiency and production costs. While impressive optimization of the latter two factors have been realized for many innovative solar cell types within the last decade, lifetime becomes a crucial issue limiting the commercial success of emerging high-performance cell types [3].

Accelerated lifetime testing of electronics has been successfully applied for many years. Also in the case of solar cells, it has served as a valuable tool allowing for an increase in lifetime by optimizing, in particular, the encapsulation of modules to protect the “PV-core” (semiconductor and electrodes) from water and oxygen [4–7]. These accelerated lifetime setups reduce the required experimental time for testing by applying extreme environmental conditions (e. g., large humidity) to the specimen. Next to environmental (or mechanical) influences, however, solar cells also degrade due to “normal use”, this means due to light exposure (and the resulting electric current and temperature increase). This fact is, in particular, true for the large number of emerging high-performance solar cell types. An accelerated testing method, which is able to assess the photostability of these materials in an acceptable experimental time (several days),

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Overcoming Electrode-Induced Losses in Organic Solar Cells by Tailoring a Quasi-Ohmic Contact to Fullerenes via Solution-Processed Alkali Hydroxide Layers

Hong Zhang, R. Clayton Shallcross, Ning Li, Tobias Stubhan, Yi Hou, Wei Chen, Tayebeh Ameri, Mathieu Turbiez, Neal R. Armstrong, and Christoph J. Brabec**

It is shown that the performance of inverted organic solar cells can be significantly improved by facilitating the formation of a quasi-ohmic contact via solution-processed alkali hydroxide (AOH) interlayers on top of *n*-type metal oxide (aluminum zinc oxide, AZO, and zinc oxide, ZnO) layers. AOHs significantly reduce the work function of metal oxides, and are further proven to effectively passivate defect states in these metal oxides. The interfacial energetics of these electron collecting contacts with a prototypical electron acceptor (C_{60}) are investigated to reveal the presence of a large interface dipole and a new interface state between the Fermi energy and the C_{60} highest occupied molecular orbital for AOH-modified AZO contacts. These novel interfacial gap states are a result of ground-state electron transfer from the metal hydroxide-functionalized AZO contact to the adsorbed molecules, which are hypothesized to be electronically hybridized with the contact. These interface states tail all the way to the Fermi energy, providing for a highly *n*-doped (metal-like) interfacial molecular layer. Furthermore, the strong "light-soaking" effect is no longer observed in devices with a AOH interface.

1. Introduction

Efficient organic solar cells (OSCs) that may ultimately become available from low-cost, lightweight, and low energy consuming roll-to-roll manufacturing processes have achieved research-cell power conversion efficiencies over 10%.[1] The physical processes involved in charge injection, extraction, transfer, and recombination at an electrode–semiconductor interface have been found to be one of the most critical factors in determining device characteristics and stability.[2]

[6,6]-phenyl-C61-butyric acid methyl ester (PCBM) is typically chosen as the electron acceptor material in OSCs, which needs to be matched by a low work function cathode to suppress interfacial losses upon extraction of electrons.[3] In the pioneering years, it has soon been found that interfacial losses and inefficient electron collection can be overcome by inserting ultrathin buffer layers of low work function, including calcium (Ca),[4] barium (Ba),[5] or lithium fluoride (LiF),[6] between the extraction electrode and the OSC active layer.

However, these cathode interlayers (Ca, Ba, or LiF) are sensitive to moisture and oxygen from the environment. The long-term stability of OSCs has rapidly evolved with the introduction of air-stable n-type inorganic metal oxides (MO_x) as electron transport layers (ETLs), including titanium oxide (TiO_x),[7] zinc oxide (ZnO),[8] or aluminum doped zinc oxide (AZO).[9] Although solution-processing of MO_x is compatible with large-area and low-price manufacturing, several material-related challenges remain. Ohyama et al. and other research groups have found that solution-processed metal oxides with hydrocarbon ligands frequently suffer from residual carbon impurities which hamper electron extraction and transfer.[10] Thermal annealing at high temperatures (>400 °C)[10] is one possibility to remove these impurities but is in conflict with the concept of roll-to-roll fabrication on polyester, where processing temperatures typically need to be maintained at less than 140 °C.[11] Having overcome the ligand limitations, Lenz et al. recently showed that the nature and the quality of the metal oxide determine the transport mechanism.[12] Defect-related energy levels or Poole–Frenkel defects

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Roll to roll compatible fabrication of inverted organic solar cells with a self-organized charge selective cathode interfacial layer†

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We successfully demonstrate a simple approach to printing efficient, inverted organic solar cells (OSCs) with a self-organized charge selective cathode interface layer based on the small-molecule **Phen-NaDPO**. Different from previous studies, **Phen-NaDPO** molecules were blended into a polymer/fullerene blend, comprising a low bandgap diketopyrrolopyrrole–quinquethiophene alternating copolymer pDPP5T-2 and phenyl-C_{61}-butyric acid methyl ester ($PC_{61}BM$), and processed by doctor blading in air. We observed a spontaneous, surface energy driven migration of **Phen-NaDPO** towards the ZnO interface and a subsequent formation of electron selective and barrier free extraction contacts. In the presence of 0.5 wt% **Phen-NaDPO**, a PCE of 5.4% was achieved for the inverted device based on an ITO/ZnO cathode. Notably, the photovoltaic performances remained at the same level with increasing the **Phen-NaDPO** concentration in the active layer from 0.25 to 1 wt%. Furthermore, this approach could be proven to effectively work with other cathodes such as bare ITO and ITO/AZO. The self-organization of **Phen-NaDPO** through spontaneous vertical phase separation is mainly attributed to its high surface energy and strong interaction with the cathode material. The present results highlight that a self-organized cathode interfacial material processed from a "ternary" active layer is fully compatible with the requirements for roll-to-roll fabrication of inverted organic solar cells.

Introduction

Organic photovoltaics (OPVs) have attracted significant academic and industrial interest due to their exceptional microstructure in combination with unique advantages such as being light-weight, flexible, transparent, and rich in color and potentially being a low-cost and easy to manufacture technology *via* roll-to-roll processing.[1–5] In this context, it is critically important to develop materials and device technologies that meet with the requirements for large-area wet processing. Over the past decade, various approaches, including the synthesis of novel materials, customized device architectures, sophisticated interface engineering and advanced processing techniques were employed to continuously improve the power conversion efficiencies (PCEs) of OPV devices.[6–9] Highly efficient OPV devices with record efficiencies above 10% were manufactured by spin-coating under inert conditions.[10–12] However, spin-coating is a batch process and as such incompatible with the visionary concept of fully printed or coated organic solar modules.

One of the relevant problems in the printed OPV technology is the formation of a selective and barrier free extraction contact at the cathode.[8,13] The most popular electron extraction layers (EELs) reported so far are based on self-assembled monolayers (SAMs),[14] conjugated and non-conjugated polymers[15,16] or alkali metal complexes,[8] which provide selective electron extraction in parallel to sufficient hole blocking functionality. However, most of these EELs are sequentially processed from solution, along with other functional layers, and are fairly thickness-sensitive.[8,15] In this context, this thickness-sensitivity is further watched with concern as it may restrict large-area high-speed roll-to-roll processing, and vulgarizes the necessity to further explore novel interfacial materials with improved optical, electrical and thermodynamic properties.[17]

It is worth noting that roll-to-roll compatible processed solar cells usually show a quite remarkable drop in efficiencies compared to spin-coated devices, highlighting the importance of the development of a stable, reliable production process which should allow a minimization of the performance

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

Chaohong Zhang, Alexander Mumyatov, Stefan Langner, José Darío Perea, Thaer Kassar, Jie Min, Lili Ke, Haiwei Chen, Kirill L. Gerasimov, Denis V. Anokhin, Dimitri A. Ivanov, Tayebeh Ameri, Andreas Osvet, Diana K. Susarova, Tobias Unruh, Ning Li, Pavel Troshin,* and Christoph J. Brabec**

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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Enhancement of up-conversion luminescence in Er,Ce doped $Y_{3-x}Yb_x$ AG single crystalline films

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ABSTRACT

The paper deals with investigation of the luminescent properties of Er and Er/Ce doped solid solutions of $Y_{1-x}Yb_x$AG garnets with x values ranging from 0 to 3.0, prepared by the LPE method in the form of single crystalline films (SCF). We have found that the effective $Ce^{3+} \rightarrow Yb^{3+}$ energy transfer is observed in the $Y_{3-x}Yb_xAl_5O_{12}$:Er,Ce garnets (Y_{3-x}YbAG:Er,Ce). Apart from that, strong enhancement of the Er^{3+} upconvesion luminescence in $Y_{3-x}Yb_x$AG:Er,Ce garnets was found due to the Ce^{3+} codoping. Among all the investigated samples of solid solutions of mixed $Y_{3-x}Yb_x$AG:Er,Ce garnets, the highest intensity of the upconversion luminescence is observed for the $Y_{1.5}Yb_{1.5}$AG:Er,Ce SCF.

1. Introduction

The $Y_3Al_5O_{12}$ garnet (YAG) is one of the most suitable hosts for Er^{3+} ion doping for laser and luminescence-related applications [1–4]. In general, when Er^{3+} ion is excited by 980 nm photons, a considerable amount of electrons is populated at the $^4I_{11/2}$ radiative level, further promoted to higher excited states, and followed by the radiative relaxation from the higher excited states are observed as up-conversion (UC) emission [5]. UC processes can convert low photon energy radiation to high energy radiation in the visible range and have found numerous applications in biological imaging, marking, therapeutics and solar cells [3,4]. However, the UC processes in Er doped YAG are strongly competing with the radiative process from the radiative $^4I_{13/2}$ level resulting in the infrared Er^{3+} luminescence around 1.53 µm [6–8].

In this work, we describe the UC processes in solid-solution of single Er and double Er,Ce doped solid-solution of $Y_{3-x}Yb_x$AG garnets at $x=0$, 1.5 and 3.0. The samples of these garnet compounds were grown in the form of single crystalline films (SCF) by the liquid phase epitaxy (LPE) method. To the best of our knowledge, Ce^{3+} and Er^{3+} co-doped $Y_{3-x}Yb_x$AG have not been investigated yet, and the effects of Ce^{3+} ion addition on the UC emission intensity in the green and red spectral ranges have not been clarified in detail.

2. Growth of SCF of $Y_{3-x}Yb_x$AG:Er and $Y_{3-x}Yb_x$AG:Ce, Er garnets and experimental technique

A set of SCFs of the solid solutions of $Y_{3-x}Yb_x$AG, $Y_{3-x}Yb_x$AG:Er and $Y_{3-x}Yb_x$AG:Ce,Er garnets with $x=0$, 1.5 and 3.0 was grown by the LPE method onto YAG substrates with (111) and (110) orientations from melt solutions based on PbO–B_2O_3 flux (see Table 1). We do not use any additional doping to decrease the misfit between the $Y_{3-x}Yb_x$ AG based SCF and the YAG substrate. The total content of garnet components in the melt solutions was 2.8–3.0 mole%. The concentration of Y_2O_3 and Al_2O_3 oxides in the melt solutions was chosen with a typical ratio of 0.3. The concentration of Er_2O_3 and CeO_2 activating oxides in the melt solutions was equal correspondingly to 0.5 and 10 mole% with respect to the total content of garnet components (Table 1). Such a large difference in the content of activating oxides is caused by the difference in the segregation coefficients of Er^{3+} and Ce^{3+} ions in YAG host (1.3–1.55 and 0.005–0.01, respectively) due to the difference in their ionic radii (1.004 Å and 1.143 Å, respectively) at the dodecahedral positions of the garnet host [9].

The structural quality of $Y_{3-x}Yb_x$AG based SCF at $x=1.5$ and 3.0 is characterized by XRD pattern (Fig. 1a and b, respectively).

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Luminescent properties of LuAG:Yb and YAG:Yb single crystalline films grown by Liquid Phase Epitaxy method

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HIGHLIGHTS

- Single crystalline films of Yb doped LuAG and YAG garnets were grown by LPE method.
- Yb^{3+} luminescence of LuAG:Yb and YAG:Yb film were studied using synchrotron radiation.
- Basic parameters of Yb^{3+} charge transfer luminescence in LuAG and YAG were determined.

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ABSTRACT

In this work, investigation of the spectroscopic parameters of the luminescence of Yb^{3+} ions in single crystalline films of $Lu_3Al_5O_{12}$ and $Y_3Al_5O_{12}$ garnets was performed using the synchrotron radiation excitation with the energy in the range of Yb^{3+} charge transitions (CT), exciton range and the onset of interband transitions of these garnets. The basic spectroscopic parameters of the Yb^{3+} CT luminescence in LuAG and YAG hosts were determined and summarized with taking into account the differences in the band gap structure of these garnets.

1. Introduction

Single crystals (SC) of $Y_3Al_5O_{12}$(YAG) and $Lu_3Al_5O_{12}$ (LuAG) garnets doped with Yb^{3+} are being considered as promising scintillators for application in the neutrino physics (Kamenskikh et al., 2003; Nikl et al., 2006). For these reasons, the luminescent properties of YAG:Yb and LuAG:Yb SCs were the subject of detailed studies in (Kamenskikh et al., 2003; Nikl et al., 2006) using the synchrotron radiation excitation. Single crystalline films (SCF) of YAG:Yb with a thickness up to 200 μm are also known as thin film disk laser media (Malinowski et al., 2001). However, by now there are no data on obtaining LuAG:Yb SCF and investigation of their luminescent properties. Systematic analysis of the features of luminescent properties of LuAG:Yb and YAG:Yb SCFs in comparison with their SC analogues is also absent. At the same time, these features can be caused by the low-temperature (<1000 °C) growth of these SCFs by the Liquid Phase Epitaxy (LPE) method as distinct from the high-temperature synthesis of SC of Yb-doped garnets from melt (Ashurov et al., 1977; Zorenko et al., 2014). Particularly, the LPE method allows one to obtain Yb doped SCF of LuAG or YAG garnet without Lu_{Al}, Y_{Al} and Yb_{Al} antisite defects and low concentration of vacancy type defects (Zorenko et al., 2005; Zorenko et al.,

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Conference Proceedings

Jens Adams, Bernd Doll, Claudia Buerhop, Tobias Pickel, Janine Teubner, Christian Camus, Christoph J. Brabec
Non-Stationary Outdoor EL-Measurements with a Fast and Highly Sensitive InGaAs Camera
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NON-STATIONARY OUTDOOR EL-MEASUREMENTS WITH A FAST AND HIGHLY SENSITIVE INGAAS CAMERA

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ABSTRACT: A fast and non-destructive failure inspection is essential to ensure the reliability of PV plants. This might only be achieved by using highly sensitive imaging techniques which can detect local electrical losses in solar modules. Here, EL imaging used for outdoor PV inspection gained large interest, since it can be used to characterize local cell damages, series resistances, and shunts in solar modules. However, currently available EL-cameras base on Si-CCD-detectors. Besides high spatial resolutions they exhibit long image integration times (IIT) of about 1 s for obtaining evaluable EL-images. To overcome this limitation we present, for the first time, an InGaAs camera which enables a complete EL-characterization of field-installed PV-modules with IITs between 1 ms and 20 ms. The short IITs result in frame rates of about 100 Hz which even offer the opportunity of recording dynamic EL-movies and daylight Electroluminescence Lock-In (ELLI) measurements. To test the outdoor applicability we compared EL-movies of the InGaAs camera with EL-images of a Si-CCD camera and show that all relevant power reducing cell failures (e. g. cracks) can be detected and characterized.

Keywords: Performance and Reliability measurement, Electroluminescence of PV Modules, Energy rating, Degradation, Ageing, Lifetime Characterization of PV Cells and Modules

1. INTRODUCTION

A fast and non-destructive failure inspection is essential for ensuring the reliability of PV plants. This might only be achieved by using highly sensitive imaging techniques which can detect local electrical losses in solar modules. Here, EL imaging used for outdoor PV inspection gained large interest, since it can be used to characterize local cell damages, series resistances, and shunts in solar modules [1–3].

State-of-the-art EL-imaging methods suffer from large image integration times (~1 s) as well as the need for a reference measurement for reducing unwanted noise signals and to obtain evaluable EL-images from PV modules. Furthermore, Si-CCD detectors show only a weak spectral sensitivity in the EL emission range of Si solar cells, since these detectors are optimized for the spectral range of visible light. All this limits a fast and effective characterization of large PV stations comprising thousands of PV modules as well as the integration of Si-CCD cameras into unmanned aerial vehicle based quality control systems. Despite a spatial resolution of less than 1 MPixel of the InGaAs detector we demonstrate evaluable EL-images with image integration times between 1 ms and 20 ms which show all important cell features. The short image integration times allow recoding EL-movies and the integration of InGaAs cameras into non-stationary characterization tools as well as the characterization of non-stationary and transient current distributions in solar cells and modules. With our work we want to demonstrate the first step of an EL-camera which can be easily integrated into a fully automatized unmanned aerial vehicle (UAV) suitable as failure control tool for large area in-flight PV station inspection. Therefore, the purpose of our work is to quantify the physical and optical limits of a fast InGaAs EL-camera which provides evaluable EL images and measurements with IIT of about 1 ms and a spatial resolution of the detector which is less than 1 MPixel. Furthermore, we want to increase the knowledge of fast EL-cameras and measurements for outdoor applications and show that our results can also be used for understanding transient changes of non-stationary current injection into solar cells, modules, and module strings. Furthermore the Electroluminescence Lock-In (ELLI) method is introduced for outdoor daylight applications. Previously, it was shown that this imaging technique is sensitive enough to detect not only several radiative recombination processes in Si solar cells but also moisture induced degradation phenomena in organic solar cells [1,4]

2. TECHNICAL DETAILS

For comparison we performed EL measurements with two different EL camera systems. The first system consisted of an EQUUS 327k N EL-camera (IRCAM GmbH, Erlangen, Germany), equipped with an InGaAs focal plane array (FPA) detector. The InGaAs detector is highly responsive in the spectral range between 0.8 µm and 1.6 µm with a spatial resolution of 640 x 512 pixels. Therefore, the frame rate can be controlled between 100 Hz for 1 ms of IIT and 50 Hz for 20 ms of IIT, respectively. The EL-camera was equipped with a 25 mm focal lens imaging system featuring a spectral transparency > 91% (IRCAM GmbH, Erlangen, Germany).

As reference EL-camera we used a standard GE 2048 2048 FI EL-camera (greateyes GmbH, Berlin, Germany), equipped with a magnesium fluoride based and front illuminated charge coupled device (CCD) detector. The CCD and FPA detector is cooled by a peltier element with a spatial resolution of 2048 x 2048 pixels. The sensor is highly responsive in the spectral range between 400 nm and 1000 nm with an absorption maximum at 700 nm. The GE 2048 2048 FI EL-camera was equipped with a planar 1.4/50 ZF-IR lens (Carl Zeiss AG, Oberkochen, Germany). To stimulate EL radiation of a module string we connected 13 modules in series to a

Impact of a large-scale market integration on the orientation of photovoltaic modules

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***Abstract*—To increase the amount of renewable energies, the Renewable Energies Act (REA) in Germany guarantees a fixed feed-in tariff for 20 years for every kilowatt-hour that is produced. Thus, photovoltaic modules were faced in the direction of the highest energy production. In this paper we investigate, if in a future energy system with a high share of renewable energy power and especially PV power, there is an incentive to face modules divergent because of an overproduction during noon. Hence, we modelled the PV generation for the states in Germany in detail as well as the spot market for the years 2014 and 2035 according to the Grid Development Plan of the German Transmission System Operators (TSO).**

I. INTRODUCTION

The Renewable Energies Act (REA) was passed a law in Germany in the year 2000 and aims to increase the amount of renewable energies in the electricity production. As a result, about 40 GWp of photovoltaics (PV) and 38 GW of wind power (WP) have been installed in the German grid at the end of 2015. Hence, in times of high wind and solar generation the renewables cover a high share of the demand for electricity. Figure 1 shows a typical course of demand and WP + PV production for the year 2014 and one can ascertain that the residual demand during noon is reduced because of the high share of PV and WP.

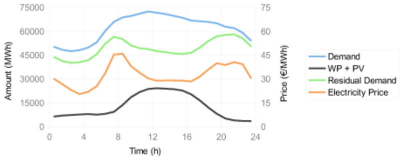

Fig. 1. Typical course of demand, renewable power generation, residual demand and electricity price at the spot market (14.05.2014)

Additionally, the so called must-run capacities produce electricity which leads to times of oversupply and therefore to low or even negative prices. Figure 1 shows a valley around noon for the course of the spot market price. With the continuing expansion of the renewables in Germany there will be times when WP and PV generation even will exceed the total demand of electricity and needs to be stored or curtailed. Therefore, in this paper we want to investigate if there is an economic benefit to shift the orientation and elevation of solar modules in an electricity system with a large-scale market integration of PV. The amount of generated electricity of these plants drop but the peak of the power generation is shifted and so the PV plants no longer produce their maximum power simultaneously.

II. MODELLING

To investigate the influence of the divergent orientations of photovoltaic modules, it was necessary to model the renewable power production for every hour of the year and the spot market at the European Energy Exchange (EEX).

A. Photovoltaics generation

Because the PV generation is an important factor, we used a detailed model that is described in the following sections.

1) Input data: Satellite measured irradiance data from the CM SAF database [1] with an spatial resolution of 0.05° longitude and 0.05° latitude were matched and averaged to the area of the states in Germany. The values for the global irradiance of the years 2010 and 2011 were used to characterize the different amount of the yearly global irradiance because the data for the year 2014 were not sufficiently complete. Although the values for the sunshine duration of the years 2010 and 2014 differ slightly (5.2 %), the global irradiance is nearly similar (0.8 %) and therefore the dataset for 2010 can be used as substitute (see Table I). The value for the year 2011 is significantly higher compared to 2010 (16.7 %) and 2014 (12.2 %). In addition, values of 500 weather stations from the German Weather Service were also matched and averaged to get temperature values. In the following sections, the scenarios using the data form 2010 are defined as *low* and the scenarios using the data from 2011 as *high*.

2) Position of the sun: The irradiance on a tilted surface is calculated according to the norm DIN 5034-2 [2] for the position of the PV plant at the longitude λ and the latitude φ. We also adapted the definition of the norm for the angle of the azimuth, which means that 180° equals south, 90° east and 270° west. For further information on calculating the necessary variables see DIN 5034-2 [2]. The sun's azimuth α_S and

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aIR-PV-check

A Quality Inspection of PV-Power Plants without Operation Interruption

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***Abstract* — *aIR-PV-check* is a method using an unmanned aerial vehicles (UAV) with an infrared (IR)-camera for the quality inspection of PV-plants under real operating conditions. It enables the fast and 100%-control of PV-plants. Defective modules are detected by their temperature distribution. Besides the meteorological conditions, the interaction of defective modules within a string influences the module performance significantly as the measured and simulated data show. Thus, modules with extremely high temperatures are predominantly expected / detected in strings with only one single defective module. Consequently, string configurations and constellations of defective modules have to be considered for evaluating the quality of modules, strings and generators.**

***Index Terms* —aerial thermography, monitoring, PV module defects, system performance.**

I. INTRODUCTION

Worldwide more than 200 GW_p photovoltaics (PV) are installed. Service and maintenance become more and more important. The interest in suitable methods for a quality check of installed PV-modules and of PV-plants increases steadily.IR-thermography is one of the methods often used. Especially measurement systems consisting of unmanned aerial vehicles (UAV) and IR-cameras are of great interest for the inspection of PV-plants.

IR-imaging is an optical method for detecting the heat radiation emitted by an object, here the solar panel. Hereby, it is fast, contactless, and non-destructive. The generated two-dimensional images enhance the localization of local heat sources, i. e. defective sites in PV-modules [1]. Mounting IR-cameras to an UAV even enhances the inspection of PV-plants [2, 3]. At ZAE Bayern, a new method for aerial inspection of PV-plants using IR-cameras mounted to an UAV has been developed - the **aIR-PV-check**. This method takes advantage of the mobility and navigability of UAVs and the fast and contactless detection of defective PV-modules. Using aIR-PV-check even large and non-accessible solar parks can be easily inspected.

During the last years the inspection of PV-plants using this technique has become very popular. IR-images show suspicious sites (modules as well as module strings) under real operating conditions, see fig. 1. This means that for the inspection the power generation of the PV generator is not interrupted, the modules do not have to be dismounted, handled or even transported for testing in a test lab. Thus, a 100% check of the performance, the functionality and the safety can be carried out for the entire PV generator.

Fig. 1 shows typical defects observed in IR-inspections of the PV generator. The two heated module strings indicate unconnected module strings (left image). The right image illustrates exemplarily the occurrence of single and multiple defective modules within a string

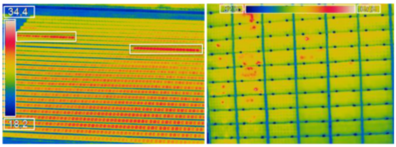

Fig. 1: IR-images of PV-plants, left: overview of PV-plant showing two irregularly heated module strings, E = 1000 W/m², T_{amb} = 35°C, right: close-up IR-view of a section of a PV-plant with several defective modules (cell fracture, bad solderings), E = 750 W/m², T_{amb} = 15°C

Typical module defects observed are cell fracture, bypassed substrings, faulty solderings, bypassed cells [4], and PID. It is suggested to characterize the defects by their temperature difference compared to a neighboring cell operating at normal temperature. Here, the influence of the real operating conditions (solar irradiance, ambient temperature, wind speed), connection scheme, mpp-tracking of the inverter on the module performance as well as on the defect temperature have to be taken into account [5-7].

During our extensive IR-inspections of installed PV-modules we observed that exceptionally high temperatures and temperature differences of defect sites occur predominantly in isolated defective modules (meaning one defective module in the entire string) [8]. Locally crucial temperatures above 95°C and higher are reached, see fig. 2.1. In the majority of cases lower defect temperatures are detected, especially when several defective modules are found within one string, compare fig. 2.2.

IR-images of PV-modules with potential induced degradation (PID) correlated to monitored string power output

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ABSTRACT

Many PV-plants suffer from potential induced degradation (PID) which causes severe power reduction of installed PV-modules. Fast and reliable methods to detect PID and evaluate the impact on the module performance are gaining importance. Drone-assisted IR-inspection is a suitable method. PID affected modules are detected by their characteristic IR-fingerprint, modules with differing number of slightly heated cells occur more frequently at the negative string end. These modules show a degraded IV-curve, lowered Voc and Isc, and electroluminescence (EL)-images with suspicious, dark cells. Also, the measured string power is reduced. For a first quantitative data evaluation the suspicious cell are counted in the IR-images and correlated with the module power. A linear decrease of the module power with increasing number of suspicious cells results. A correlation function for estimating the module power was deduced, which has a mean deviation of less than 7%. This correlation function allows an acceptable approximation of the string power.

Keywords: IR-inspection, IR-imaging, PV-modules, PV-plants, PID, potential induced degradation, electroluminescence, reliability, degradation

1 INTRODUCTION

A published interview with several PV-plant operators operating 20% of the PV-plants in Germany addresses potential induced degradation (PID) as a severe problem. They state that 160 MWp of their PV-plants are affected by this failure [1] and cause significant power loss.

PID is a fairly young failure type in PV-modules. It occurs when high negative voltages are present in the PV-plants, predominantly towards the end of long strings at high voltages exceeding 800 V. As recent studies show, the shunt resistance of the solar cells is reduced in the case of PID [2]. The migration of sodium ions is discussed as possible fault reason leading to a degradation or even short-circuiting of the pn-junction. However, all investigations agree that operating the installed modules at high temperatures, in high humidity and at high voltages [3] favors the occurrence of PID [4-6]. EL-imaging is suitable to visualize the PID affected cells [6]. The affected cells are darker than the other, well operating cells. The intensity describes the state of degradation: The darker the cell the more the cell is degraded. IV-curves of PID affected modules reveal that the open circuit voltage V_{oc} decreases at the first stage, then the fill factor decreases and finally the short-circuit current I_{sc} is reduced.

For the detection of PID in installed PV-plants frequently outdoor EL-imaging is used and the IV-curves, or at least V_{oc} or I_{sc} are measured [7]. This procedure is very time-consuming because of the electrical contacting necessary for the EL-measurements and it suffers from the performance at night due to the better detection of the weak EL-signal. Furthermore, EL-imaging of PV-modules has to be carried out at night in order to achieve a sufficient signal-to-noise ratio for the low intensity EL signal.

Drone-assisted IR-imaging of the installed PV-plants could constitute a practical and fast alternative [8, 9]. Temperature differences and irregular temperature distributions caused by defective modules can be detected by aIR-PV-check, a method using an unmanned aerial vehicle (UAV) with a highly resolving IR-camera for the systematic inspection of PV-plants under operation. IR-imaging provides several advantages: the PV-plants can be inspected during operation and

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Statistical overview of findings by IR-inspections of PV-plants

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ABSTRACT

First statistical evaluation of IR-inspections of PV-plants reveals that 86% of the installed PV-plants show IR-abnormalities. More than 120 PV-plants with more than 160,000 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 8% and for module strings approximately 4%. The differentiation between the installation locations reveals that small residential installation show relatively more defective modules than large field installations. – Therefore, 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-images, statistics, PV-modules, defects, failure, substrings

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. Some focus more on the degradation rates of different technologies [1, 2], others on the influence of various climatic regions on the PV-installation [3, 4]. Also, there are various surveys of failure rates of PV-modules during operation [5-11].

Among the top ten module failure mechanisms are: connector failures and glass breakage as retrieved from field inspections [10]. The presented data suggest 34% of the inspected modules have some type of failure. The IEA report [5] 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 [7] 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 [11]. Most investigations focus on the impact on the actual power output. The effect on the module power output differs with the failure type.

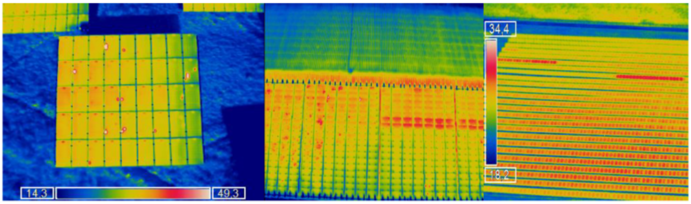

Figure 1: IR-images of different PV-plants showing certain numbers of sites with elevated temperature, left: tracked PV-table with 12 out of 45 modules showing IR-abnormalities, center: industrial roof with numerous defective modules and two suspicious module strings, right: IR-overview of a field installation 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, non-destructive inspection under real operation conditions

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Correlation between the Generated String Powers of a Photovoltaic Power Plant and Module Defects Detected by Aerial Thermography

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***Abstract* — Drone-based aerial thermography has become a convenient quality assessment tool for photovoltaic power plants. Often caused by defective photovoltaic modules and cells, thermal abnormalities can be localized and classified. So far, infrared images cannot be utilized for the quantitative estimation of the generated power of a solar park yet. In this context, three photovoltaic power plants with an overall nominal power of approximately 9.4 MW$_p$ are evaluated. The analysis of both the radiometric data and the monitoring data of the inverters indicate a strong correlation between defective modules and the power of the associated string.**

***Index Terms* — aerial thermography, monitoring, PV module defects, system performance.**

I. INTRODUCTION

At the end of 2015, about 1.5 million photovoltaic (PV) systems with an overall nominal power of approximately 40 GW were installed in Germany, temporarily covering up to 35 % of the instantaneous power consumption on sunny workdays [1]. As a consequence, short-term, middle-term, and long-term predictions of the performance of PV systems take on greater significance. Considering the necessary continuous maintenance of such a high number of installed PV systems, there is the need for efficient quality assessment tools.

In this context, infrared (IR) thermography is a contactless, non-destructive and fast assessment tool that can be used to evaluate the quality of PV modules under operating conditions. Thermal abnormalities in IR images of PV modules such as hot spots or hot areas indicate irregularities which are probably caused by defects in the PV module [2]-[5]. In recent years, remote-controlled unmanned air vehicles (UAV) have been used increasingly to attain aerial IR recordings of large PV power plants with which thermally suspicious PV modules can be clearly localized [6]-[7]. In particular, one or more inactive substrings within one PV module previously identified in an aerial IR image correlate with a reduced string current in the associated string [8].

As of today, aerial IR recordings cannot be utilized for a quantitative estimation of the instantaneous power of a PV power plant under operating conditions yet. With regard to future monitoring and early detection systems for PV power plants, this work aims at providing a solid basis for such estimation by making use of both the aerial IR data and the monitoring data of the inverters.

II. EXPERIMENTAL PROCEDURE

A. Test Objects

Test objects are three PV power plants in northern Bavaria, Germany, which were commissioned for the first time in April 2012, June 2012, and April 2013, respectively. The PV power plants have an overall nominal power of 9,357.7 MW$_p$ and consist of 40,720 PV modules in total.

Installed on flat terrain, the polycrystalline modules have a nominal power ranging from 225 W$_p$ to 240 W$_p$. One module has 60 solar cells and three bypass diodes (each for 20 solar cells on the left side, the center, and the right side). One string consists of 20 modules connected in series.

Each of the 509 inverters (SMA STP 17000 TL-10) handles four strings (I1-I4) and has two maximum power point (MPP) trackers (MPPT A and B, respectively). MPPT A tracks the MPP of the strings I1-I3 connected in parallel, whereas MPPT B tracks the MPP of the string I4.

Fig. 1. The remote-controlled octocopter with integrated IR and RGB cameras used for the generation of the aerial IR data.

B. Data Acquisition

For the generation of the aerial IR recordings, a remote-controlled octocopter with an extensive navigation system (DaVinci Copters Scarabot X8) is used (see Fig. 1). Two

NON-UNIFORMITY MEASUREMENTS OF A STEADY STATE SOLAR SIMULATOR USING THE HISHIKAWA-HASHIMOTO METHOD AND SUBSEQUENT IMPROVEMENT

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ABSTRACT: A steady state solar simulator has been set up at the ZAE Bayern. The system is meant to be used for the characterization of photovoltaic (PV) of various technologies. In particular, it can be used for pre-conditioning of thin film modules in order to enable reliable power and *I-V* measurements. Furthermore, it allows for determining the temperature coefficient of PV modules of various technologies. The latter application will also be discussed in this work. Here, the optimization of the steady state solar simulator based on a method originally introduced by Hishikawa et al. for pulsed solar simulators is described and the results of this optimization are presented.

Keywords: Characterization, Experimental Methods, Light-Soaking, Qualification and Testing

1 INTRODUCTION

A typical steady state solar simulator consists of various components that influence the distribution of the light: usually several lamps, mirrors, reflectors and other optical components. Therefore, the task to optimize the solar simulator towards good uniformity of the irradiation is very time consuming because traditionally the measurement is done using the short circuit current values of one or more solar cells moved over the entire area.

In 2008 Hishikawa et al. [1] presented a method to measure the lateral homogeneity of pulsed solar simulators using a camera based system in very short time. In this manuscript, we present the use of this technique to measure and improve the lateral non-uniformity of a steady state solar simulator for an accelerated adjustment of the lamps of the solar simulator and other optical components. The raw measurements of the camera are corrected for the optic's influences and the measurement method is validated using the traditional method of scrolling a reference cell over the one sun plane.

Using this technique, a steady state solar simulator for full-size PV modules is built up with a low non-homogeneity value, resulting in good measurement and test results.

2 TECHNICAL DETAILS

The steady state solar simulator illuminates an area of 200 cm x 170 cm at an intensity of approximately 1 sun. It constitutes of six halogen-metal vapor lamps of 2000 W each, which are operated via electronic ballasts. The system runs at 32 A three phase current, which is distributed to the electronic ballasts and the cooling fans via an automatic circuit breaker. The setup also consists of an air ventilation system for heat removal and two mirrors at the sides of the setup for adjusting the homogeneity of the illumination.

For safety reasons, the UV part of the irradiation was artificially cut off. The setup is built in a mobile version so that it can be moved freely within the building.

3 EXPERIMENTAL DETAILS

The uniformity measurement was done after the Hishikawa-Hashimoto method reported in [1]. The technique consists of measuring the irradiance distribution in the plane of one sun two dimensionally using a Panasonic DMC-FZ45 digital camera with consecutive analysis with a computer and classification according to the standard IEC 60904-9 with respect to the desired class A, B or C. The analyzed areas of one sun with an irradiance of 1000 W/m² (Fig. 1) are either 160 cm x 150 cm or 120 cm x 120 cm large.

In order to characterize the homogeneity of the distribution of the steady state solar simulator's irradiation a homogeneously colored grey cloth was fixed in the illuminated module plane. The intensity distribution obtained from this illuminated cloth served as basis for further analysis of the irradiation emitted by the lamps.

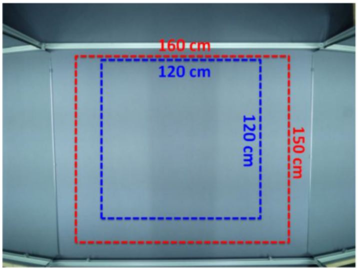

Figure 1: Digital camera image of a grey cloth in the module plane with non-optimized optical configuration and two different analyzed one sun areas with edge length of either 160 cm x 150 cm or 120 cm x 120 cm.

To show the power of the technique the raw measurement image of a non-optimized configuration is shown in Fig. 2 a) (Fig. already converted into W/m²). Clearly brighter

Automatic Detection and Analysis of Photovoltaic Modules in Aerial Infrared Imagery

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Abstract

Drone-based aerial thermography has become a convenient quality assessment tool for the precise localization of defective modules and cells in large photovoltaic power plants. However, manual evaluation of aerial infrared recordings can be extremely time-consuming. Therefore, we propose an approach for automatic detection and analysis of photovoltaic modules in aerial infrared images. Significant temperature abnormalities such as hot spots and hot areas can be identified using our processing pipeline. To identify such defects, we first detect the individual modules in infrared images, and then use statistical tests to detect the defective modules. A quantitative evaluation of the detection and analysis pipeline on real-world infrared recordings shows the applicability of our approach.

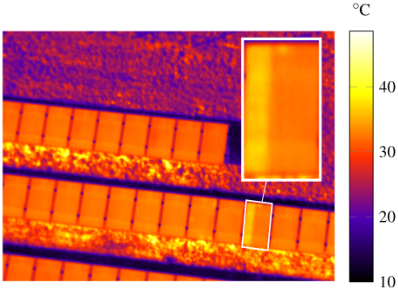

Figure 1. Radiometric aerial infrared image data of a photovoltaic power plant displayed in false color. The left substring of the marked photovoltaic module is inactive.

1. Introduction

Over the last decade, the market for photovoltaic systems has grown tremendously. In Germany alone, about 1.5 million photovoltaic systems with an overall peak power of approximately 38.5 GW were installed at the end of 2014 [1]. Considering the necessary continuous maintenance of such a high number of installed photovoltaic modules, there is a need for efficient quality assessment tools.

Particularly in recent years, operators and investors of photovoltaic power plants started appreciating the benefits of infrared thermography. Infrared imaging is time-saving, non-destructive, and contactless. These features allow an easy data acquisition under real operating conditions. In infrared images of photovoltaic modules, temperature abnormalities such as hot spots and hot areas indicate irregularities, which are often caused by defects in photovoltaic modules [2, 3, 4, 5]. In combination with remote-controlled unmanned air vehicles (UAVs), infrared thermography is therefore an especially convenient quality assessment tool for the precise localization of defective photovoltaic modules and cells in large photovoltaic power plants [6, 7]. Fig. 1 shows radiometric aerial infrared image data of a solar power plant acquired using a drone.

Despite the technical progress, aerial infrared imagery is still analyzed mostly manually, which can be extremely time-consuming. With regard to future monitoring and early detection systems for photovoltaic power plants, this work aims at bringing forward the automatic evaluation of aerial infrared recordings.

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High temperature solution growth of SiC by the Vertical Bridgman method using a metal free Si-C-melt at 2300 °C

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Keywords: SiC, solution growth, high temperature growth, metal free, surface morphology, Vertical Bridgman, Vertical Gradient Freeze

Abstract. We developed a solution growth process related to the combination of the Vertical Bridgman and Vertical Gradient Freeze in a metal free Si-C melt at growth temperatures of 2300 °C. For this procedure we present a detailed description of the growth process and discuss the influence of different growth parameters on the surface morphology and growth rate. So far, we managed to grow SiC layers with a thickness up to 300 µm. The characterization of the crystal morphology was carried out using SEM images and the metal concentration was estimated using SIMS.

Introduction

In recent years, solution growth of bulk SiC material has faced a process revival. Since the first large scale solution growth attempts in the late 1990s [1], a number of fundamental as well as advanced technologic reports have been given [2][3][4]. Basically all current reports have in common to apply top seeded solution growth which is a derivative of the well-known Czochralski growth process. In order to increase the carbon solubility and, hence, to increase growth velocity at moderate temperatures around 1500 °C to 1700 °C, metals like Cr and Al are added to the Si-C solution. In this paper we follow an alternative process which applies bottom seeded solution growth that is related to the combination of the Vertical Bridgman and Vertical Gradient Freeze growth process at high temperatures of approximately 2300 °C without solvent metals.

Due to the knowledge of the authors, so far no reports are available in literature on stable solution growth of SiC from a pure Si-C melt using the above described high temperature ($T>>2000$ °C). It is believed that the absence of solvent metals in order to increase the carbon solubility will be very beneficial for the future growth of electronic grade SiC from the solution. At the same time, the Vertical Bridgman and in particular the Vertical Gradient Freeze technology has proved to be a reliable growth method for a number of other semiconductor materials that are naturally grown solely from the melt. Transferring this growth method to a high temperature regime of 2300 °C as demonstrated within this work is encountered as very promising technology for SiC solution growth.

Experimental

Solution growth was carried out in an inductively heated graphite container at temperatures between 2200 °C and 2300 °C (Fig. 1(a)). For the experiments we used 6H single crystal seeds with an off axis angle of 5° and a diameter of 30 mm prepared in our own lab using physical vapor transport growth. The seeds were fixed at the bottom of the graphite crucible with the carbon-face up. Afterwards we filled the crucible with electrical grade silicon granules leading to a melt height

FAILURE CLASSIFICATION OF DEFECTIVE PV MODULES BASED ON MAXIMUM POWER POINT ANALYSIS

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ABSTRACT: Photovoltaic (PV) modules are often affected by defects caused by transport and installation or by field degradation due to environmental conditions. If a power reduction is observed in the inverter data, a detailed error cause analysis is often very cost-intensive even when using imaging methods like thermography or electroluminescence. We present a method to classify the defect type of PV modules only by evaluating the maximum power output (P_{mpp}) for different irradiances. Thereby, low parallel resistance, high series resistance and broken cells can be distinguished from each other. Simulations and consistent explanations confirm the experimental findings. The method works particularly well for parallel resistance problems like potential induced degradation (PID). Thus, this failure type can easily be diagnosed in modules. The method should also be applicable to data of module strings and to thermography-based failure analysis in field which will be investigated in the future.

Keywords: Defects, Degradation, Photovoltaic, PV Module, Simulation

1 INTRODUCTION

Photovoltaic modules often exhibit power reduction due to failures. However, for the classification of the failures the modules have to be transported to laboratories or expensive tests have to be performed in field. In this paper, we introduce a method for classifying the defect in a PV module based on simplified *I-V* curve analysis.

2 METHODS, MODELS AND MATERIALS

The *I-V* curves of the crystalline silicon (c-Si) modules were measured at different irradiances at 25 °C with the Spire Solar's Spi-Sun Simulator™ 4600SLP (class AAA performance). The classification of the module defects was done by using the *I-V* curves and the electroluminescence (EL) images of the modules. 12 defect modules plus 4 defect-free reference modules from 4 manufactures were selected for the investigations. The EL images showed usually more than one defective cell in a module. Exemplarily the EL images and the measured *I-V* curves for different irradiances are shown for the three defect types in Figure 1.

The simulations were performed qualitatively using the circuit simulator LTspice (version 4) from Linear Technology. The equivalent circuit consisted of 60 cells modelled with the one-diode model and 3 bypass diodes for the substrings. The simulation parameters are listed in Table 1.

Table1: Simulation parameters of defect-free cells

Parameter	Value
Photocurrent I_{ph}	5 A
Series resistance R_{s}	5 mΩ
Parallel resistance R_{p}	150 Ω
Saturation current I_{s}	$6.2 \cdot 10^{-8}$ A
Ideality factor n	1.28

3 EXPERIMENTS

From the *I-V* curves the power outputs at maximum power point (P_{mpp}) of the modules were determined for different irradiances. The modules were classified into three defect types: 1) low parallel resistance, 2) high series resistance and 3) broken cells. The low parallel resistance R_{p} (e.g. due to poorly isolated cell edges) were simulated by reducing the R_{p} to 3.16 Ω and 1 Ω in one or all 60 cells. For the series resistance defect type, R_{s} of the substring was increased to 0.2 Ω and 0.32 Ω in one or all three substrings. A broken cell was simulated by connecting the broken cell part in parallel to the residual main cell via a contact resistance R_{contact} as described in [1], because broken cell parts are only seldom completely disconnected in reality. The broken cell area was assumed to be 30 %. R_{contact} was set to 1 Ω, 3.16 Ω and 10 kΩ in one or all 60 cells.

4 RESULTS AND DISCUSSION

Plotting the relative maximum power P_{mpp} of a defective module referred to a non-defective reference module (*relative* $P_{\mathrm{mpp}} = P_{\mathrm{mpp,bad}} / P_{\mathrm{mpp,reference}}$) versus the irradiance reveals a positive slope in the case of low parallel resistance problems like PID, bad cell edge isolation or shunts (cf. Figure 2a). In our case, modules 1–5 revealed cells with bad edge isolation. For other defect types like high series resistance or cell breakage, the curves decrease with increasing irradiance (cf. Figure 2b and Figure 2c). The high series resistances in modules 6–9 are due to solder or contact failures of the busbars in the cells as diagnosed by EL images. The kink in the curve of module 6 is caused by one shunted cell in the module additionally to the cells with solder failures. Modules 10–12 were affected by broken cells.

These experimental findings could be qualitatively verified by simulations where one cell or all cells in the module were simulated as being defective (cf. Figure 3). Like in Figure 2a, the simulated curves in Figure 3a show an increase in *relative* P_{mpp} with irradiance for low parallel resistance failure. For one defect cell the deviation from one is small but visible. When all cells of the module are affected, the reduction in *relative* P_{mpp} is large for low irradiance and vanished for higher irradiances, as is seen in Figure 3a. For series resistance

Highly Efficient, Large Area, Roll Coated Flexible and Rigid Solar Modules: Design Rules and Realization

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***Abstract* — Large area, roll-to-roll printed solar modules are presented in literature with power conversion efficiencies (PCE) well below hero solar cells produced in the lab. Here we show how to design a proper layout to minimize the electrical losses and how to evaluate optical losses induced by the substitution of the sputtered/evaporated electrodes with solution processable ones. Highly efficient, large area, roll-produced solar modules are then shown, achieving PCEs above 4.2% on total area on flexible and of 5.3% on glass substrates. A record-breaking geometric fill factor of 98.5% is demonstrated, thanks to ultra-fast laser structuring.**

***Index terms* — Simulation, large area modules, no losses, organic photovoltaics, printed photovoltaics**

I. INTRODUCTION

Printed photovoltaics (pPV) technologies have increasingly attracted the interest of the scientific community due to several aspects: potential reduction of production costs, high throughput obtainable, pleasant appearance and semi-transparency. Aesthetic beauty and customization allow for many different applications, not possible with other, traditional photovoltaic technologies[1].

However, one major drawback of pPV is the power conversion efficiency (PCE); despite the dramatic efficiency improvements, which lead organic photovoltaics (OPV) to reach over 10%[2] PCE and perovskite based ones over 20%[3], large area, roll-to-roll produced modules show much lower PCEs[4]. In order for these technologies to be successful in the market, it is necessary to reduce the gap of efficiency between lab-scale, small-area solar cells and large-area, roll-to-roll (R2R) produced modules. In this contribution we will focus on describing how optical simulations, *via* Transfer Matrix Formalism (TMF), can estimate losses induced by the replacement of standard evaporated/sputtered electrodes with solution processed ones. We will then show our approach using Finite Element Simulations (FEM), to minimize the parasitic resistances hidden in monolithically interconnected cells and design an optimum structure for a solar module. Finally we will show how OPV modules prepared using these design rules achieve efficiencies up to 93% of the reference, hero modules by successfully combining high precision slot-die coating and ultra-short pulse laser structuring.

II. OPTICAL SIMULATIONS

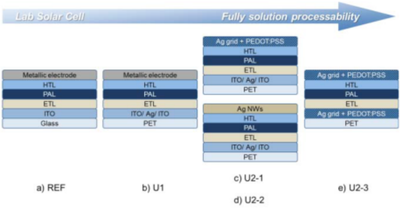

Fig.1. Path from lab-scale solar cells to fully solution processable, upscalable devices. a) Shows the reference (REF) architecture, composed of an ITO sputtered electrode and evaporated Ag electrode; structure b) has an ITO–Ag–ITO (IMI) electrode whereas c) and d) use a different top electrode (Ag grid/PEDOT and Ag NWs, respectively). Structure e) shows the replacement of the IMI electrode with an Ag grid/PEDOT composite electrode.

The up-scaling process of small-area, lab-produced cells to modules involves the substitution of thick, brittle and evaporated electrodes with electrodes compatible to R2R production techniques. In Fig. 1 several structures of solar cells are reported; REF is the structure most commonly used for reference, small-area cells employing a sputtered ITO electrode and an evaporated Ag top electrode. Structure U1 shows a cell where ITO has been replaced with an ITO/ Ag/ ITO electrode,[5] whereas in structure U2-1 the metallic top electrode has been replaced by a composite electrode (PEDOT:PSS and Ag grid). Structures U2-2 and U2-3 show the substitution of the top electrode with silver nanowires (AgNWs) and of the bottom electrode with the PEDOT:PSS/Ag grid electrode respectively.

Optical simulations were performed with different photoactive layers[6], assuming IQEs constant and equal to 80%. The results are shown in Fig. 2.

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Proceedings Article

Inkjet printing of semitransparent electrodes for photovoltaic applications

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Zakya H. Kafafi; Paul A. Lane; Ifor D. W. Samuel
San Diego, California, United States | August 28, 2016

Abstract References

abstract

In this work we compare two different semitransparent inkjet printed electrodes for organic photovoltaic (OPV) applications. We highlight the processing as well as layer properties of the most commonly used silver grid/PEDOT:PSS electrodes and a newly developed inkjet printed silver nanowire (AgNW) mesh. Application of the different electrode types in fully inkjet printed organic solar cells reveals the superior performance of the AgNWs. Using them as bottom and top electrode, semitransparent solar cells with power conversion efficiencies (PCE) of up to 4.3 % are demonstrated. Comparable devices with silver grid electrodes reach a maximum PCE of 3.6 %. We identify shading of the opaque silver grids, which cover ~10 % of the device area, and thermal stress introduced by the curing of the silver grid top electrodes as main factors for the losses. Furthermore, the silver grids do not only lower the short circuit current of the solar cell, but are also visually obstructive.

The newly developed inkjet printed AgNW percolation network electrodes show high transparency of over 90 % at a sheet resistance of less than 20 Ω/□ and a very low haze of less than 3 %. This enables a clear view through semitransparent devices like organic light emitting diodes (OLEDS) or solar cells in which they can be used.

Topics

Electrodes ; Inkjet technology ; Silver ; Solar cells ; Organic light emitting diodes ; Organic photovoltaics ; Resistance ; Transparency ; Networks ; Opacity

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Inkjet printing of highly conductive nanoparticle dispersions for organic electronics

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***Abstract*: Inkjet printing of conductive nanoparticle dispersions and their use in organic electronic devices for multiple purposes like contact pads and electrodes is demonstrated. In this context, we show the printing of semitransparent silver grid/Poly(3,4-ethylene-dioxythiophene) :poly(styrenesulfonate) (PEDOT:PSS) electrodes and their application in organic photovoltaics (OPV). The cell performance was optimized using finite element simulations accounting for electrical and optical layer properties as well as resolution restrictions given by the inkjet. Furthermore, we demonstrate inkjet printing of silver nanowires (AgNW) and their use as percolation electrode. Characterization reveals low sheet resistance of less than 20 Ω/□ together with a high specular transmittance of more than 90 %, indicating the excellent quality of the inkjet printed layers. Applying them as cathode and anode, fully inkjet printed semitransparent solar cells with power conversion efficiencies (PCE) of up to 4.3 % on an active area of > 1 cm² are demonstrated.**

Keywords: inkjet; organic photovoltaics; semitransparent electrode; silver grid; silver nanowires; PEDOT:PSS

I. INTRODUCTION

Inkjet printing as a large scale manufacturing method is widely known from packaging and textile industries and is increasing in popularity in the printed electronics sector. Reasons for the expansion of this printing technology are the low material consumption, the freedom of shape as well as the simplicity to change the printing pattern combined with high possible throughput speeds of more than 1000 m²/h [1].

One technology which can benefit from this potential is OPV (Fig. 1). As low processing temperatures enable high throughput roll-to-roll fabrication on flexible substrates and the drop on demand (DOD) technique makes any post structuring process unnecessary, whole solar modules can be produced at low cost. Furthermore, in comparison to the common silicon solar cells, OPV offers the fabrication of semitransparent devices, which can easily be integrated in various elements of daily life like buildings, cars and even textiles.

However, industrial inkjet printing of such electronic devices imposes strict requirements with respect to the inks and processing conditions. Well printable inks have to fulfill certain criteria regarding density, viscosity and surface tension. An early significant work by Fromm [2], [3] about the mechanisms of drop generation identified the Ohnesorge number (Oh), which sums the mentioned physical properties, as central parameter for a stable drop formation.

$$Oh = \frac{\sqrt{We}}{\text{Re}} = \frac{\eta}{\sqrt{L * \rho * \sigma}} \tag{1}$$

- Oh: Ohnesorge number
- We: Weber number
- Re: Reynolds number
- η: dynamic viscosity

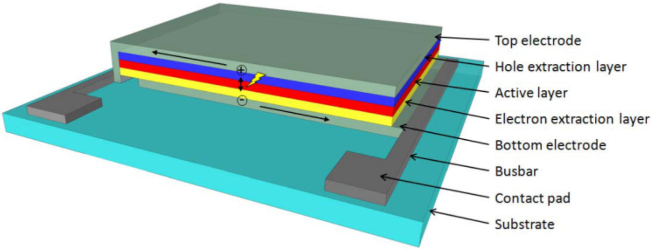

Fig. 1. Typical structure of an inverted organic solar cell.

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Physical vapor growth of double position boundary free, quasi-bulk 3C-SiC on high quality 3C-SiC on Si CVD templates

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Keywords: Quasi-bulk, 3C-SiC, DPBs free, seeded sublimation epitaxy, seed transfer/stabilization

Abstract. We have developed and investigated the quasi-bulk crystal growth of 3C-SiC on transferred, high quality, CVD-grown templates using a sublimation sandwich technique. The 3C-SiC seeding template layers grown on silicon were removed from the silicon carrier using a solution of hydrofluoric acid, nitric acid and water and glued to a SiC substrate using carbon glue. The transferred layers were used as seeding material to grow high quality, single crystalline, double position boundary free 3C-SiC crystals with thicknesses of up to 860 µm and a size of 18 x 20 mm. Analysis of the bulk-like 3C-SiC layers was carried out using Laue measurement in back-reflecting geometry, Raman spectroscopy and optical microscopy.

Introduction

The 3C polytype of SiC shows technological challenges for the bulk growth. However, a significant step for electronic devices like MOSFETs [1] and intermediate band solar cells [2] can be predicted if high quality material can be produced in large amounts. A promising technique could be the seeded sublimation epitaxy or related methods (like the fast sublimation growth process). Due to a lack of high quality seeding layers, this technology has not yet been available. To achieve a high crystalline quality in the growth process the seed should: (i) contain no double positioning boundaries (DPBs) and (ii) feature a decent mechanical stability. A big problem is the elimination of DPBs in 3C-SiC. Therefore, the epitaxial enlargement of a perfect crystal-layer grown using the CVD method would be preferable. By this technique, 12 to 50 µm thick 3C-SiC layers grown on a particularly structured silicon substrate with single domain [3] were achieved leading to an annihilation of DPBs in the first hundred nanometers of growth. In this work, we transfer such layers on different substrates and enlarge them using a sublimation epitaxial related technique [4].

Experimental Setup

The 3C-SiC (001) seeding material was grown on a four-inch silicon wafer [3] cut into less or equal to 15x15 mm^2 pieces using a single wire diamond saw. To remove the silicon carrier we used a solution of hydrofluoric acid, nitric acid and water (HF:HNO$_3$:H$_2$O) in a concentration ratio of 1:1:0.5. For an increased mechanical stability we coated the backside of the 3C-SiC seeding layer

Computational Optimization and Solution-Processing of Thick and Efficient Luminescent Down-Shifting Layers for Photovoltaics

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ABSTRACT

Luminescent down-shifting (LDS) is a simple, powerful tool for increasing the range of solar irradiance that can be efficiently utilized by photovoltaic devices. We developed an optical model to simulate the ideal optical properties (absorbance, transmittance, luminescence quantum yield, etc.) of LDS layers for solar cells. We evaluated which quantum efficiencies and which optical densities are necessary to achieve an improvement in solar cell performance. In particular we considered copper indium gallium diselenide (CIGS) devices. Our model relies on experimentally measured data for the transmission and emission spectra as well as for the external quantum efficiency (EQE) of the solar cell. By combining experimental work with this optical model, we aim to propose an environmentally friendly technology for coating thick (300-500 µm), efficient luminescent down-shifting layers. These layers consist of polyvinyl butyral (PVB) and organic UV-converting fluorescent dyes. The absorption coefficients and luminescence quantum yields of the dyes were determined both in a solution of the solvent benzyl alcohol and in the solid polymer layers. This data shows that the dyes retain luminescence quantum yields of approximately 90% after solution-processing. The produced layers were then applied to CIGS solar cells, thereby improving the EQE of the devices in the UV region. At a wavelength of 390 nm, for instance, the EQE increased from 18% to 53%. These values closely agree with the theoretically calculated ones. The proposed technology, thus, provides a pathway toward efficient, fully solution-processable encapsulated photovoltaic modules.

Keywords: luminescence, absorbance, organic dye, quantum yield, EQE, photovoltaics

1. INTRODUCTION

The transition towards a sustainable energy supply requires photovoltaic devices (PV) with improved performance[1]. Luminescent down-shifting (LDS) is one of the approaches to achieve that. It increases the response of solar cells in the UV spectral region via photoluminescent processes[2]. This is usually done by incorporating luminescent materials into transparent binder and placing such a layer in front of a solar cell. As most of the modern solar cells do not perform well in UV, the employed luminescent materials should absorb incident UV radiation and emit visible light. In most cases this light is utilized by the solar cells more efficiently, thus, increasing the overall performance of the device[2].

Although the LDS principle is already a few decades old, fairly simple and an entirely optical approach, it has several limitations that prevent an application in PV industry. Firstly, luminescence down-shifting materials have typically quantum yields (PLQY) less than 100 %. Also many luminescent materials have insufficient Stokes shift to avoid reabsorption[3]. Therefore, not all of the absorbed incident UV light is reemitted and escapes an LDS layer. Secondly, the re-emitted light escapes the LDS layer not only in the direction of the underlying solar cell but also through the sides and the top[2, 4]. And thirdly, if the size of the incorporated luminescent material is larger than 10 - 50 nm, it causes scattering and increases back-reflection losses of the incident visible light[5, 6]. Hence, the so-called LDS efficiency, η_{LDS}, which is a product of the transmittance of the visible light, PLQY and optical efficiency of LDS layers[4], reaches only about 72 % for the most thoroughly optimized cases[7].

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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-stoichiometric. 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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Solar driven energy conversion applications based on 3C-SiC

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Keywords: cubic silicon carbide (3C-SiC), solar cell, photoelectrochemical (PEC) water splitting

Abstract. There is a strong and growing worldwide research on exploring renewable energy resources. Solar energy is the most abundant, inexhaustible and clean energy source, but there are profound material challenges to capture, convert and store solar energy. In this work, we explore 3C-SiC as an attractive material towards solar-driven energy conversion applications: (i) Boron doped 3C-SiC as candidate for an intermediate band photovoltaic material, and (ii) 3C-SiC as a photoelectrode for solar-driven water splitting. Absorption spectrum of boron doped 3C-SiC shows a deep energy level at ~0.7 eV above the valence band edge. This indicates that boron doped 3C-SiC may be a good candidate as an intermediate band photovoltaic material, and that bulk like 3C-SiC can have sufficient quality to be a promising electrode for photoelectrochemical water splitting.

Introduction

Solar energy can provide sufficient power for the global energy demands if it can be efficiently harvested and stored. The photovoltaic cell is the most common device to collect solar energy. The intermediate-band (IB) solar cell, designed by introducing an energy band or level in the semiconductor bandgap, has attracted much attention due to its promising properties to achieve a very high efficiency. The theoretical model for an IB solar cell [1] predicts a maximum efficiency of 63% in an ideal material having a bandgap at 1.95 eV with an intermediate level at ~0.7 eV above the valence band edge or below the conduction band edge. Cubic silicon carbide (3C-SiC) is a very attractive material for IB solar cells because it has a bandgap of ~2.36 eV and a deep impurity given by the boron acceptor level at ~0.7 eV above the valence band.

Further on, a direct conversion of solar energy into hydrogen from photoelectrochemical (PEC) water splitting provides another attractive, clean and sustainable way to harvest and store solar

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Application of in-situ 3D computed tomography during PVT growth of 4H-SiC for the study of source material consumption under varying growth conditions

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*corresponding author

Keywords: SiC bulk growth, in-situ X-ray visualization, 3D computed tomography.

Abstract. 2D and 3D in-situ X-ray visualization was applied to study the behavior of the SiC source material during PVT growth under various growth conditions. Experiments were carried out in two growth chambers for the growth of 3 inch and 4 inch crystals. Growth parameters were varied in the gas room in terms of axial temperature and inert gas pressure. The study addresses the stability of the SiC source material surface. It is shown that a higher inert gas pressure (e.g. 25 mbar) inhibits an unintentional upward evolution of the SiC feedstock that interferes with the crystal growth interface. The latter is related to a suppression of a pronounced recrystallization inside the SiC source. For a low inert gas pressure (e.g. 10 mbar) it is concluded that the axial temperature gradient inside the source material needs to be decreased to less than ca. 10 K/cm.

Introduction

Within recent years, the physical vapor transport (PVT) growth process of SiC has become a mature growth technology. SiC single crystals with a diameter of 4 inch and 6 inch with low defect densities are state-of-the art (see e.g. [1]). Current applied research topics include p-type doping, lateral overgrowth of defects and the application of new types of SiC powder source materials. In this work we present the application of in-situ 3D computed tomography to follow the SiC source material consumption under varying growth conditions, i.e. decrease of the inert gas pressure. A low inert gas pressure is of particular interest for PVT growth at around 2000 °C in order to keep the growth rate at a reasonable value well above 100 μm/h.

Experiments

Crystal growth of SiC was carried out in a 3 inch and in a 4 inch graphite growth cell at ca. 2150 °C to 2200 °C with a growth rate between 200 μm/h to 500 μm/h. Growth conditions were tuned for stable 4H-SiC growth. In particular medium nitrogen doping was performed which improves polytypes stability [2]. The experimental setup of the in-situ 3D computed tomography (CT) has been described in detail in [3]. As brief summary: As X-ray source a 125 kVp tungsten anode tube (spot size 70 μm, maximum cw current = 350 μA) was used. As X-ray detector a flat panel device (PaxScan 2520 D/CL, Varian Medical Systems) was applied. 3D image processing by the so called Feldkamp algorithm was carried out using 200 to 400 2D X-ray projection images which were acquired during rotation of the growth setup interior by 360°. The final 3D images exhibit a spatial resolution of ca. 125 μm. In-situ 3D x-ray images of the 3 inch setup are based on the described CT. In the case of the 4 inch growth runs, in-situ and ex-situ 2D X-ray analysis was carried out [4].

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, December 2016
Print ISBN: 978-3-319-28336-4, Online ISBN: 978-3-319-28338-8
DOI: 10.1007/978-3-319-28338-8_13

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. 293-310, December 2016
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

Date: 21 December 2016

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

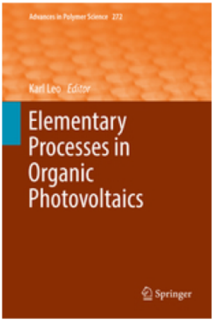
Tayebeh Ameri, Michael Forster, Ullrich Scherf, Christoph J. Brabec

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.



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

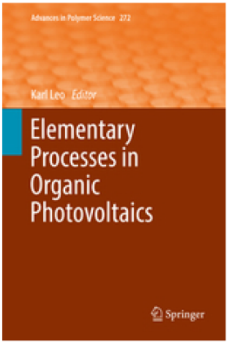
21 December 2016

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.



9. Presentations at Conferences, Workshops, Events

Abdelhaleem, Soraya

02.-06.05.2016
European Materials Research Society (EMRS) Spring Meeting, Lille, France
Poster presentation: *Surface Morphology Improvement of Non-vacuum Deposited CZTS Nano-particles Absorber Layer by Selenization Process*

Ameri, Tayebeh

26.-27.02.2016
1st annual Inter-University (FUM & Kassel University) Workshop on Electrical Engineering, Mashhad, Iran
Invited talk: *Organic photovoltaics; fundamentals, novel concepts and recent progress*

23.-24.05.2016
FAU-DESY jLAMs Kick-off Workshop, Hamburg, Germany
Talk: *Ternary IR Sensitization of Polymer:Fullerene Systems, Microstructure, Transport and Stability*

05.-08.04.2016
5th SolarTech International Conference, Munich, Germany
Talk: *Hybrid polymer solar cell based on PbS quantum dots / carbon nanotube nanoarchitectures*

15.07.2016
Christiane-Nüsslein-Volhard Stiftung meeting, Tübingen, Germany
Talk: *Printed Organic and Hybrid Ternary Photovoltaics: Fundamentals of Morphology and Transport*

30.09.2016
4th progress meeting of OSNIRO project, Eindhoven, Netherlands

24.-26.10.2016
Global Congress & Expo on Materials Science & Nanoscience, Dubai, UAE
Invited talk: *Near IR sensitization of polymer/fullerene solar cells; a multifunctional concept to boost power conversion efficiency*

23.-25.11.2016
3rd International Congress Next Generation Solar Energy Meets Nanotechnology, Erlangen, Germany

27.11.2016-02.12.2016
The 2016 MRS Fall Meeting & Exhibit, Boston, USA
Talk: *Origin of the VOC in Organic Ternary Solar Cells*

02.12.2016
Iowa State University, Ames, USA
Talk: *Near IR sensitization of polymer/fullerene solar cells; a multifunctional concept to boost PCE*

Brabec, Christoph J.

04.02.2016
Center of Advanced Materials, University Heidelberg, Germany
Invited talk: *Next Generation Materials and Concepts for Photo and X-Ray Detectors*

08.02.2016
Siemens Technology Council, Cambridge, United Kingdom
Invited talk: *Next Generation Solar Energy Concepts*

24.02.2016
World Sustainable Energy Days, Wels, Austria
Invited talk: *Novel concepts for photovoltaic facades*

21.03.2016
Heeger Symposium Linz, University of Linz, Austria
Invited talk: *Bulkheterojunction Solar Cells*

20.04.2016
THINFACE Conference, Marie & Pierre Curie Universität Paris, France
Invited talk: *Lifetime and Stability of Hybrid and Organic Solar Cells*

12.05.2016
SFB 951 Hybrdi Structures, Humboldt Universität Berlin, Germany
Invited talk: *Solution Processed Semiconductor Composites for Energy Applications*

25.05.2016
Plenary, International Workshop on Organic Electronics and Photovoltaics, Porquerolles, France
Plenary: *Burn-in Effect Instabilities in Organic and Hybrid Solar Cells*

13.06.2016
Nature Energy Conference, Wuhan, China
Invited talk: *Stability and Lifetime of Photovoltaics*

24.06.2016
Institute of Materials Research and Engineering (IMRE), Singapore, Asia
Invited talk: *Energy Materials for a Renewable Future*

27.06.2016
The International Conference on Science and Technology of Synthetic Metals in 2016 (ICSM 2016), Guangzhou, China
Invited talk: *Overcoming Burn-in Losses in Organic Solar Cells*

01.07.2016
International Conference on Hybrid and Organic Photovoltaics (HOPV16), Swansea, United Kingdom
Invited talk: *Material and Stability Aspects of Perovskite Solar Cells*

05.-06.07.2016
Nanotexnology 2016 ISFOE 2016, Thessaloniki, Greece
Plenary: *Materials and Concepts for Printed Photovoltaics Technologies*
Invited talk: *Exploring the lifetime limitations of organic solar cells*

13.07.2016
Fhg Conference Series “Mensch und Technik”, Erlangen, Germany
Plenary: *Über die Zukunft der PV*

10.10.2016
Energiematerialien, Helmholtz-Zentrum Berlin, Berlin, Germany
Invited talk: *Organic and Hybrid Energy Materials*

08.11.2016
Conference “Fundamentals and Device Physics of Organic Semiconductors”, Milano, Italy
Invited talk: *Non Fullerene Acceptors for Organic Electronics*

22.11.2016
3rd Generation Solar Energy Conference, Erlangen, Germany
Welcome Presentation: *The Future of Renewable Energies in Germany*

23.11.2016
3rd Generation Solar Energy Conference, Erlangen, Germany
Invited talk: *On the Photo- and Device Physics of Non Fullerene Acceptors*

28.11.2016
University de Valle, Materials Cluster, Colombia, Republic of Colombia
Invited talk: *Organic Photovoltiacs: Fundamentals, Microstructure, Materials and Aspects*

30.11.2016
University de Valle, Physics Department, Colombia, Republic of Colombia
Invited talk: *Advanced Material Concepts for Photovoltaic Energy Conversion*

Bronnbauer, Carina

27.06.2016
The International Conference on Science and Technology of Synthetic Metals in 2016 (ICSM 2016), Guangzhou, China
Talk: *Fully printed semitransparent light emitting diodes with adjustable emission direction for window application*

05.07.2016
Nanotexnology 2016 ISFOE 2016, Thessaloniki, Greece
Talk: *Fully printed semitransparent light emitting diodes with adjustable emission direction for window application*

Burlafinger, Klaus

11.-12.07.2016
iSEneC 2016 - Integration of Sustainable Energy Conference, Nürnberg, Germany
Poster: *Ultrafast screening method for assessing the photo-stability of thin film solar cells*

11.-12.07.2016
iSEneC 2016 - Integration of Sustainable Energy Conference, Nürnberg, Germany
Poster: *Ultrafast screening method for assessing the photo-stability of thin film solar cells*

Chepyga, Liudmyla

23.-25.11.2016
3rd International Congress Next Generation Solar Energy Meets Nanotechnology, Erlangen, Germany

Classen, Andrej

23.-25.11.2016
3rd International Congress Next Generation Solar Energy Meets Nanotechnology, Erlangen, Germany

Doll, Bernd

20.-24.06.2016
32nd European Photovoltaic Solar Energy Conference and Exhibition, Munich, Germany
Poster presentation: *Non-Uniformity Measurements of a Steady State Solar Simulator Using the Hishikawa-Hashimoto Method and Subsequent Improvement*
Poster presentation: *Non-Stationary Outdoor EL-Measurements with a Fast and Highly Sensitive InGaAs Camera*

Fecher, Frank

20.-24.06.2016
32nd European Photovoltaic Solar Energy Conference and Exhibition, Munich, Germany
Poster presentation: *Failure classification of defective PV Modules based on maximum power point analysis*

Forberich, Karen

07.04.2016
Fortbildungsveranstaltung für PhysiklehrerInnen, ?, ?
Talk: *Solarzellen der 3. Generation*

21.09.2016
Workshop Bauwerkintegrierte Photovoltaik, Energie Campus Nürnberg , Nürnberg, Germany
Poster: *Printed dielectric mirrors for semi-transparent solar cells*

22.-23.09.2016
3rd Euroregional Workshop on Photovoltaics & Nanophotonics, Lubljana, Slowenien
Invited talk: *Dielectric mirrors for printed solar cells*

Gao, Shuai

23.-25.11.2016
3rd International Congress Next Generation Solar Energy Meets Nanotechnology, Erlangen, Germany
Poster: *Solution Processed Nanoparticles-Based Flexible and Transferable Dielectric Mirrors*

Gasparini, Nicola

13.-15.06.2016
12th International Conference on Organic Electronics (ICOE), Bratislava, Slovakia
Talk: *Highly efficient ternary organic solar cells with suppressed parasitic recombination, rendering an unprecedented large FF of 77%*

13.-15.06.2016
International Conference of Electroluminescence and Optoelectronic Devices (ICEL), Raleigh (North Carolina), USA
Talk: *Counterintuitive design rules yield ternary OPVs with reduced recombination*

Gu, Ening

23.-25.11.2016
3rd International Congress Next Generation Solar Energy Meets Nanotechnology, Erlangen, Germany

Hassanien, Ayat

02.-06.05.2016
European Materials Research Society (EMRS) Spring Meeting, Lille, France
Poster presentation: *Effect of Annealing Conditions on Structural, Optical Properties and Surface Morphology of Cu2ZnSnS4 Nanoparticles Absorber Thin Films Synthesized by Solvothermal Method*

He, Yakun

23.-25.11.2016
3rd International Congress Next Generation Solar Energy Meets Nanotechnology, Erlangen, Germany

Heiss, Wolfgang

23.-25.11.2016
3rd International Congress Next Generation Solar Energy Meets Nanotechnology, Erlangen, Germany
Talk: *Quasi-epitaxial metal-halide perovskite ligand shells on PbS nanocrystals*

Kahmann, Simon

04.-09.09.2016
CMD26 - The 26th Conference of the Condensed Matter Division of the EPS, Groningen, Netherlands
Talk: *Ultrafast Energy Transfer Boosts the Performance of a Ternary Organic Solar Cell Approaching 10% Efficiency*

23.-25.11.2016
3rd International Congress Next Generation Solar Energy Meets Nanotechnology, Erlangen, Germany
Poster presentation: *Polarons in Narrow Band Gap Polymers Probed over the Entire Infrared Spectral Range*

Killilea, Niall

02.-05.08.2016
Nanocrystals Conference, Dublin, Ireland
Invited talk: *High Performance IR Photo-Detectors Based on PbS Nanocrystals with Epitaxialy Coherent 0D Perovskite Clusters Ligand Shell*

Langner, Stefan

23.-25.11.2016
3rd International Congress Next Generation Solar Energy Meets Nanotechnology, Erlangen, Germany
Poster presentation: *Environmentally benign highly efficient organic solar cells*

Levchuk, Ievgen

28.08.-01.09.2016
SPIE Optics + Photonics 2016, San Diego, California, USA
Talk: *Organometallic perovskites for optoelectronic applications*

28.08.2016-01.09.2016
SPIE Optics + Photonics, Sand Diego, USA
Talk: *Deciphering the role of impurities in methylammonium iodide and their impact on the performance of perovskite solar cells*
Talk: *Coloring semitransparent room-temperature fabricated perovskite solar cells via dielectric mirrors*

26.-28.09.2016
2nd International Conference on Perovskite Solar Cells and Optoelectronics (PSCO-2016), Genova, Italy
Talk: *Unraveling the role of methylammonium iodide impurities in perovskite precursor solution and their impact on the performance of solar cells*

21.-23.11.2016
8th EAM Symposium, Kloster Banz, Bad Staffelstein, Germany
Poster presentation: *En route towards efficient ternary blends in BHJ Solar Cells*

23.-25.11.2016
3rd International Congress Next Generation Solar Energy Meets Nanotechnology, Erlangen, Germany
Poster presentation: *En route towards efficient ternary blends in BHJ Solar Cells*

Li, Ning

20.-24.04.2016
International Workshop on Advanced Materials and Processes for Energy Applications, Istanbul, Turkey
Invited talk: *Towards large-scale production: processing perspectives on highly efficient organic solar cells*

23.-24.05.2016
FAU-DESY jLAMs Kick-off Workshop, Hamburg, Germany
Talk: *Solution-Processed Organic Photovoltaics: Interface, Morphology and Stability*

26.06-01.07.2016
The International Conference on Science and Technology of Synthetic Metals in 2016 (ICSM 2016), Guangzhou, China
Talk: *Triple-junction Hybrid Solar Cells with a Combined Parallel and Series-interconnection*

14.07.2016
HI-ERN Project Meeting in 2016, Nürnberg, Germany
Talk: *Towards a Hybrid Tandem Technology*

13.-23.09.2016
E-MRS 2016 Fall Meeting, Warsaw, Poland
Keynote talk: *Exploring the potential of printed organic photovoltaics technologies*
Invited talk: *Interface Engineering for Organic and Hybrid Multi-junction Solar Cells*

23.-25.11.2016
3rd International Congress on Next Generation Solar Energy Meets Nanotechnology, Erlangen, Germany

Liu, Chao

23.-25.11.2016
3rd International Congress Next Generation Solar Energy Meets Nanotechnology, Erlangen, Germany

Lucera, Luca

05.-10.06.2016
IEEE 43rd PVSC, Portland, USA

Maisch, Philipp

28.08.2016-01.09.2016
SPIE Optics + Photonics, Sand Diego, USA
Talk: *Inkjet Printing of Semitransparent Electrodes for Photovoltaic Applications*

28.-29.09.2016
Internationaler Kongress Molded Interconnect Devices 2016 (MID), Würzburg, Germany
Talk: *Inkjet printing of highly conductive nanoparticle dispersions for organic electronics*

27.11.2016-02.12.2016
The 2016 MRS Fall Meeting & Exhibit, Boston, USA
Talk: *Scalable organic solar module fabrication– a comparison of digitally printed and LASER patterned interconnects*

Matt, Gebhard

23.-25.11.2016
3rd International Congress Next Generation Solar Energy Meets Nanotechnology, Erlangen, Germany

Perea Ospina, Jose Dario

23.-25.11.2016
3rd International Congress Next Generation Solar Energy Meets Nanotechnology, Erlangen, Germany
Poster presentation: *Environmentally benign highly efficient organic solar cells*

14.12.2016
University of Quindio, Armenia, Quindío, Colombia
Talk: *Thermodynamics, Electrical and Transport Determination of conjugated Polymers*

Richter, Moses

06.-11.03.2016
DPG Tagung Frühjahrstagung 2016, Regensburg, Germany
Poster presentation: *Electrical Conduction in Thin Layers of ZnO Nanoparticles, Studied Under Various Conditions*

23.-25.11.2016
3rd International Congress Next Generation Solar Energy Meets Nanotechnology, Erlangen, Germany
Poster presentation: *Long Term Stability of Organic Solar Cells by an UV-enhanced ZnO Interlayer*

Salvador, Michael

29.03.-01.04.2016
MRS Spring Meeting, Phoenix, Arizona
Talk: *Antioxidants Increase the Photooxidation Stability of Organic Photovoltaic Polymers and Blends*

26.06.-01.07.2016
The International Conference on Science and Technology of Synthetic Metals in 2016 (ICSM 2016), Guangzhou, China
Talk: *Antioxidants Increase Resilience of Organic Photovoltaic Polymers and Blends towards Photooxidation*

02.-05.10.2016
International Conference of Electroluminescence and Optoelectronic Devices (ICEL), Raleigh (North Carolina), USA
Talk: *Antioxidants enhance the Photooxidation Stability of Semiconducting Polymers and Blends*

Schimmel, Saskia

16.-18.03.2016
1st German Czechoslovak Conference on Crystal Growth (GCCCG-1/DKT2016), Dresden, Germany
Talk: *Solubility and dissolution kinetics of GaN under ammonobasic conditions using NaN3 mineralizer*

02.-07.10.2016
International Workshop on Nitride Semiconductors, Orlando, USA
Talk: *GaN Solubility and Dissolution Kinetics Investigated Using Direct Insight into Ammonothermal Autoclaves by In Situ X-Ray Imaging*

12.-13.10.2016
DGKK-AK „Massive Halbleiterkristalle“, Erlangen, Germany
Talk: *Towards Improved Understanding of Ammonothermal Crystal Growth - Insights by In Situ X-ray Imaging of GaN Dissolution*

Schuster, Matthias

02.-06.05.2016
European Materials Research Society (EMRS) Spring Meeting, Lille, France
Talk: *Optoelectronic Properties of Transparent Conductive Thin Films Using ITO and ZnO Nanoparticles, Sol-Gel-ZnO and Ag Nanowires*
Poster: *Processing and Characterization of Vacuum-Free CuInSe2 Solar-Cell-Absorbers Using Nanoparticle-Precursors and Different Temperature Treatment Techniques*

Shrestha, Shreetu

26.-28.09.2016
2nd International Conference on Perovskite Solar Cells and Optoelectronics, Genoa, Italy
Poster presentation: *X-ray detectors based on sintered MAPbI3 micro-particles*

23.-25.11.2016
3rd International Congress Next Generation Solar Energy Meets Nanotechnology, Erlangen, Germany
Poster presentation: *X-ray detectors based on sintered MAPbI3 micro-particles*

Solodovnyk, Anastasiia

13.-18.02.2016
SPIE Photonics West 2016, San Francisco, USA

Spyropoulos, George D.

23.-25.11.2016
3rd International Congress Next Generation Solar Energy Meets Nanotechnology, Erlangen, Germany

Vetter, Andreas

11.-12.07.2016
ISEneC 2016 Integration of Sustainable Energy Conference, Nürnberg, Germany
Poster presentation: *Ultrafast screening method for assessing the photo-stability of thin film solar cells*

Zhang, Chaohong

23.-25.11.2016
3rd International Congress Next Generation Solar Energy Meets Nanotechnology, Erlangen, Germany
Poster presentation: *Overcoming the Thermal Instability of Efficient Polymer Solar Cells by Employing Novel Fullerene-Based Acceptors*

27.11. - 02.12. 2016
The 2016 MRS Fall Meeting & Exhibit, Boston, USA
Talk: *Overcoming the Thermal Instability of Efficient Polymer Solar Cells by Employing Novel Fullerene-Based Acceptors*

10. Seminar Presentations

Chair Seminar

12.01.2016
Kevin Baderschneider (Bachelor thesis report)
Einfluss von Beschichtungsmethoden und Tintenformulierung auf die optischen und elektrischen Eigenschaften von Silber Nanodraht Schichten

26.01.2016
Arne Riecke (Doctoral thesis report)
Silicon nanoparticles: From solution-processing towards crystalline layers

23.02.2016
Armin Heinrichsdobler (Doctoral thesis report extern, OSRAM OLED GmbH)
Inkjet printed polyimide for OLED substrates

Daniel Riedel (Doctoral thesis report extern, OSRAM OLED GmbH)
Simulation of OLED devices with internal light extraction layers

22.03.2016
Bernd Doll (Master thesis report)
Investigation of the film formation of doctor bladed pervoskite layers for solar cell application as a function of humidity

05.04.2016
Shreetu Shrestha (Doctoral thesis report)
Organic inorganic Perovskite based direct X-ray detectors

Julian Hornich (Doctoral thesis report)
Numerical study of plasmonic absorption enhancement in organic semiconductor absorbers

12.04.2016
Negar Kazerouni (Master thesis report)
High efficient organic ternary solar cells, case study on open circuit voltage (Voc)

Laraib Khanzada (Doctoral thesis report)
Characterization of solution-processed CZTS solar cells

19.04.2016
Michael Salvador (Postdoc report)
Degradation mechanisms in OPV

Qifan Xue (Doctoral thesis report)
Morphology control and Interfacial Engineering in Perovskite Solar Cells

10.05.2016
Eric Tam (Doctoral thesis report)
Silver nanowire electrodes for inkjet-printed solar cells and modules

Klaus Burlafinger (Doctoral thesis report)
Development of a high power illumination setup for accelerated photo-degradation of thin film solar cells

17.05.2016
Fei Guo (Postdoc report)
Color-tunable OLEDs

24.05.2016
Haiwei Chen (Doctoral thesis report)
Stability of Perovskite Solar Cells

Shi Chen (Doctoral thesis report)
Exploring the limiting open-circuit voltage and the voltage loss mechanism in planar CH3NH3PbBr3 perovskite solar cell

31.05.2016
Carina Bronnbauer (Doctoral thesis report)
Printed dielectric mirrors for organic electronics

Liudmyla Chepyga (Doctoral thesis report)
YAG:Dy/Er phosphors for high temperature measurements

07.06.2016
Johannes Hepp (Doctoral thesis report, ZAE)
Quality control of thin film solar cells using imaging and spectral methods

14.06.2016
Amjad Ali (Doctoral thesis report)
Phosphors for thermography

21.06.2016
Mario Prosa (Doctoral thesis guest report)
Investigation of recombination layers in organic tandem solar cells

Jie Min (Postdoc report)
Side-Chain Engineering for Enhancing the Properties of Small Molecule Solar Cells

28.06.2016
Ingo Paulke (Master thesis report)
Spektraloptische Messungen an CIGS-Solarzellen zur Inline-Qualitätskontrolle

05.07.2016
Ievgen Levchuk (Doctoral thesis report)
Nanoparticles for Solar Cells

12.07.2016
Jonas Reuther (Master thesis report)
Electrical characterization of organic solar cells at low temperatures

19.07.2016
Ening Gu (Doctoral thesis report)
Solution processed CIGS solar cell

13.09.2016
Stefan Langner (Doctoral thesis report)
Green formulations for organic solar cells

Jose Dario Perea Ospina (Doctoral thesis report)
Thermodynamic, Electric and Transport Properties of Organic Conjugated Semiconductors by Quantum Chemistry Methods

20.09.2016
Chen Xie (Doctoral thesis report)
Green solvent-processed organic solar cells based on polymer:fullerene nanoparticles

04.10.2016
Simon Kahmann (Doctoral thesis report)
Low energy pump-probe spectroscopy on nanomaterials for solar cells

18.10.2016
Philipp Maisch (Doctoral thesis report)
Inkjet printed organic solar modules

Jessica Gast (Master's thesis report)
Development of phosphor layers for contactless measurement of temperature via thermal imaging

25.10.2016
Nicola Gasparini (Doctoral thesis report)
Charge carrier recombination in ternary organic solar cells

08.11.2016
Iftikhar Channa (Doctoral thesis report)
Solution processable barrier materials for encapsulation of OPV

22.11.2016
Shuai Gao (Doctoral thesis report)
Stretch-tunable dielectric mirrors

Chaohang Zhang (Doctoral thesis report)
Organic solar cells based on novel fullerene acceptors: higher Voc and excellent thermal stability

Yakun He (Master thesis report)
Preparation of Nanofibrous Composite Proton Exchange Membranes and Adjustment of the Microstructures

29.11. 2016
Steffen Leimbach (Bachelor thesis report)
Nanocrystals for light up-conversion

Chao Liu (Master thesis report)
Enhanced Power-Conversion Efficiency in Inverted Bulk Heterojunction Solar Cells using Liquid Crystal Conjugated Polyelectrolytes Interlayer

06.12.2016
Bernd Doll (Doctoral thesis report)
Introduction: Quantitative EL-measurement tool for PV-Modules in daylight

Armin Haase (Doctoral thesis report, WW2)
Morphology and Electrical Properties of Doped Diamond

13.12.2016
Markus Pröll (Doctoral thesis report)
Vorläufige Abschlussergebnisse der Diss./Forschungsprojektes

Andrej Classen (Doctoral thesis report)
Solar cells based on carbon nanotubes and a short overview on MIS-CELIV and transient photoconductivity

20.12.2016
Johannes Bergmann (Master thesis report)
Processing of hybrid organic-inorganic perovskite ink: from powder to device Application

Sandra Pallach (Master thesis report)
Degradation of organic photodiodes under x-ray irradiation

Visitors & Guest Talks

12.01.2015
Dr. Daniel Abou-Ras (Helmholtz-Zentrum Berlin für Materialien und Energie)
Correlative approaches for the multiscale analysis of thin-film solar cells by electron microscopy

09.02.2016
Dr. rer. nat. Philip Schulz (Guest lecture, National Renewable Energy Laboratory, Golden, CO)
Engineering the Energetics in Organic Photovoltaics and Organic Lead Halide Perovskite Solar Cells

01.03.2016
Prof. Bryce Richards (Guest lecture, Karlsruher Institut für Technologie (KIT))

03.05.2015
Prof. Dr. Koen Vandewal (Guest talk, Institut für Angewandte Photophysik Technische Universität Dresden)
Charge-transfer states for organic solar cells and near-infrared photo-detectors

17.05.2016
Prof. Dr. Clemens Peter Simbrunner (Universität Bremen)
Towards epitaxial perovskite layers

20.07.2016
Prof. Weber (Max Planck Institut, Mainz)
Local Time-Dependent Charging in a Perovskite Solar Cell

15.12.2016
Dr. Sergey Lemeshko (Regional Sales manager, NT-MDT Spectrum Instruments)
New developments in scanning probe microscopy towards extreme resolution

11. Conferences organized by Members of the Institute

Brabec, Christoph J.

23-25.11.2016
Next Generation Solar Energy
Heinrich Lades Halle, Erlangen, Germany
Organisation: Prof. Brabec, Prof. Heiss (i-MEET), Prof. Hirsch (Org Chemie), Prof. Halik (OMD), Prof. Pflaum (Informatik), Prof. Guldi (Physikalische Chemie)

27-28.10.2016
Klausur- und Strategietagung der Werkstoffwissenschaften
Behringermühle, Gößweinstein, Germany
Organisation: Geschäftsstelle und Sprecher des Departments

11-12.07.2016
Integration of Sustainable Energy Conference ISEneC 2016, PV Session
Messezentrum Nürnberg, Germany

Egelhaaf, Hans

22.09.2016
Building Integrated PV Tag
Energiecampus EnCN, Nürnberg, Germany
Organisation: ZAE Bayern

12. Cooperation in Committees

Ameri, Tayebeh

Associate Editor of Frontiers in Energy Research

Brabec, Christoph J.

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,....)

Serving as expert referee for European Community

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 Board of the International Conference on Organic Electronics (ICOE) & Organizer of the 11th ICOE conference, Erlangen

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

Solodovnyk, Anastasiia

Member of Graduate School in Advanced Optical Technologies (SOAT) Friedrich-Alexander-Universität Erlangen-Nürnberg

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

Advanced Optical Technologies (SAOT) (Germany)
January 2013 – December 2016

Advanced Optical Technologies (SAOT) (Germany)
July 2014 – June 2016
Light Propagation in Phosphor-Filled Layers for Photovoltaic Application

Bayerische Forschungsstiftung, AZ-1006-11 (Germany)
July 2012 – May 2016
Intelligenz im Solarglas

Bayerische Forschungsstiftung, DOK-170-14 (Germany)
01.04.2014 – 31.03.2017
Entwicklung neuer Leuchtstoffe für die Hochtemperatur-Thermometrie

COLCIENCIAS (Columbia)
1 November 2014 – 30 September 2018
(Perea Ospina, Jose Dario)

CONACYT (The Mexican National Council for Science and Technology) (Mexico)
August 2013 – August 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 No. 201204910209
The Interfacial Layer of Organic Solar Cells (Zhang, Hong)

CSC grant:
Tang, Xiaofeng
Chen, Haiwei
Chen, Shi
Chen, Xie
Gao, Shuai
Gu, Ening
Zhang, Chaohong

DFG: BR 4031/6-1 (Germany)
January 2016 – December 2017
Entwicklung von neuen bildgebenden Verfahren zur Defekterkennung in Tandem Solarzellen

DFG SPP 1355 BR 4031/2-1 and 2-2 (Germany)
01 September 2010 – 31 December 2016
Elementarprozesse der organischen Photovoltaik:
Controlling the electronic interface properties in polymer-fullerene bulk-heterojunction solar cells.

DFG WE 2107/6-2 (Germany)
01 January – 31 December 2017
In situ Visualisierung des ammonothermalen Kristallisationsprozesses mittels Röntgenmesstechnik

EnCN (7502184) (Germany)
September 2011 – 31 December 2016
Solarfabrik

Exzellenzcluster: B1 (Germany)
01 November 2012 – 31 October 2017
Printable solar cells

GRK1896 (Germany)
01.01.2014 – 31.12.2016
In-Situ Microscopy with Electrons, X-ray and Scanning Probes

Helmholtz (Germany)
01.01.2014 – 31.12.2016
Rekombination in bleifreien Perovskite-Solarzellen

HI-ERN Joint Projects, DBF01253 (Germany)
01.01.2014 - 31.12.2016
Rekombination in bleifreien Perowskit-Solarzellen

MATSOL Energie Campus Nürnberg (Germany)
01 January 2013 – 31 December 2016
Ultraharte Gläser
Beschleunigte Testverfahren
Optik – Optoelektronik
Testlabor / Prüflabor Materialkontakte und Interfaces
Thermophysikalische Auslegung

OSNIRO FP7-PEOPLE-2013-ITN (Germany)
01 October 2013 – 31 December 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

Real Nano (Germany)
2015-2016
FFG Programm Produktion der Zukunft

SFB 953 B01 (Germany)
01 January 2012 – 31 December 2016
Synthetic Carbon Allotropes

Solprocel (Germany)
01 November 2013 – 31 October 2016
Solution processed high performance transparent organic photovoltaic cells

SolTech StMWFK (Germany)
25 July 2012 – 31 July 2017
Solar technologies go hybrid

Staedtler Stiftung WW/eh 13/15 (Germany)
01 June 2015 – 31 October 2016
Wachstum von Silizium-Germanium-Karbid Halbleiterschichten mittels Chemischer Gasphasenabscheidung für Photovoltaikanwendungen

UOS (Germany)
01 September 2013 – 31 August 2016
Umweltverträglicher Beitrag der Nanotechnologie zur Energiewende

Virtuelle Hochschule Bayern 14-l-03-14Wel1 (Germany)
01 January 2015 – 29 February 2016
Werkstoffkunde für Elektrotechnik/Materialien der Elektronik und Energietechnik

14. Teaching

Winter Term 2015/16

Lectures (VORL)

Grundlagen der Halbleiterphysik, *W. Heiß*

Grundlagen des Kristallwachstums und der Halbleitertechnologie, *P. Wellmann*

Materialien der Elektronik und der Energietechnik, *P. Wellmann*

Materialien und Bauelemente für die Optoelektronik und Energietechnologie: Grundlagen [MaBaOpEnGr], *Ch. J. Brabec*

Nano-Bauelemente-Sensoren, MEMS, Micromachining [(NanoDev)], *A. Vetter*

Nanospektroskopie [NanoSpek], *W. Heiß, M. Batentschuk*

Photophysics and Electronic Transport [PhPhys], *H.-J. Egelhaaf, Ch. J. Brabec, M. Halik*

Photovoltaik-Technologie, *Th. Kunz*

Technische Grundlagen medizinischer Diagnostikverfahren [TGMDV], *M. Thoms*

Werkstoffe und Verfahren der medizinischen Diagnostik I, *M. Thoms*

Werkstoffkunde für Studierende der Elektrotechnik (EEI) [Werkstoffk.(ET)], *P. Wellmann*

Exercises and laboratory courses (PR, PJS, UE)

Lab Work Organic Electronics, *T. Ameri*

Lab Work Organic Electronics NT, *M. Batentschuk*

Praktikum Materialien der Elektronik und der Energietechnologie (5.Sem.) [PR2-ET], *P. Wellmann, M. Batentschuk*

Praktikum Funktionswerkstoffe in der Energietechnologie [PFE], *P. Wellmann*

Praktikum Nanotechnologie 2 (Master), *W. Heiß, E. Spiecker*

Praktikum Transporteigenschaften in HL [PrTrpeHL], *M. Batentschuk*

Praktikum Wahlfach Crystal Growth, *P. Wellmann*

Praktikum Werkstoffe 2 WS 2015 2016 [PW2], *M. Batentschuk*

Projektarbeit - Arbeitsgemeinschaft Kristallisation von SiC und CIS [AG SiC CIS], *P. Wellmann*

Projektarbeit – Arbeitsgemeinschaft Organische Photovoltaik [AG OPV], *Ch. J. Brabec*

Übung Nano Devices [(ÜbNanoDev)], *A. Vetter*

Seminars (AWA, SEM)

Anleitung zur wissenschaftlichen Arbeit, *T. Ameri*

Kern-/ Nebenfachseminar i-MEET (für Studierende im 3. MA-Semester) [SEM], *Ch. J. Brabec, E. Meißner*

Neuere Fragen zu Werkstoffen der Elektronik und Energietechnologie, *Ch. J. Brabec, P. Wellmann, M. Batentschuk*

Seminar "Organic Electronics" [SOE], *T. Ameri*

Seminar on Solar Energy [SemSolE], *CH. Pflaum, Ch. J. Brabec, J. Hornich*

Seminar über Bachelor- und Masterarbeiten, *Ch. J. Brabec*

Seminar über Bachelor-, Master und Doktorarbeiten – Crystal Growth, *P. Wellmann*

Solution Processed Semiconductors [SoPSem], *W. Heiß*

Summer Term 2016

Lectures (VORL)

Devices [Dev], *Ch. J. Brabec, G. Matt,*

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], *M. Batentschuk, G. Matt, E. Meißner, K. Forberich, A. Osvet*

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*

Organic Electronics-Devices [OE-Dev], T. Ameri

Technologie der Züchtung von Halbleiterkristallen und Photovoltaik [ZHLPV], *J. Friedrich*

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)

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 [LS-Pra], *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 [AGK-Sem 2], *P. Wellmann*

Projektarbeit - Arbeitsgemeinschaft Lösungsprozessierte Halbleiter [AG HL-Sem], *Ch. J. Brabec*

Übungen zu elektrische, magnetische und optische Eigenschaften ET [EOM-Ü-ET], *W. Heiß*

Übungen zu elektrische, magnetische und optische Eigenschaften NT/MWT [EOM-Ü-NT/MWT], *W. Heiß*

Seminars (SEM, SL)

Seminar Druckbare Elektronik [DrEl-Sem], *M. Batentschuk*

How to start a company [HSC-Sem], *Ch. J. Brabec*

Kernfachseminar [KF-Sem], *Ch. J. Brabec*, *M. Batentschuk*

Neuere Fragen zu Werkstoffen der Elektronik und Energietechnologie (Lehrstuhl-Seminar) [iMEET-Sem], *Ch. J. Brabec*, *P. Wellmann, M. Batentschuk*

Seminar on Solar Energy [SolarSem], *Ch. Pflaum, Ch. J. Brabec, J. Hornich*

Seminar on Solar Energy_Sondertermin [SolSem], *Ch. Pflaum, Ch. J. Brabec, J. Hornich*

Seminar "Organic Electronics" [OE-Sem 1], *T. Ameri*

Seminar über Bachelor- und Masterarbeiten [BMBr-Sem], *Ch. J. Brabec*

Seminar über Bachelor- und Masterarbeiten (Wellmann) [BMWe-Sem], *P. Wellmann*

Vorbesprechung zum Masterstudium am i-MEET [iMEET-Vb-Ma], *M. Batentschuk, Ch. J. Brabec*

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*

15. Addresses and Maps

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Materials for Electronics and Energy Technology
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Fax: +49 (0) 9131 85-28495
E-Mail: i-meet@ww.uni-erlangen.de
Internet: http://www.i-meet.ww.techfak.fau.de

<u>**By car**</u>:
Highway A3 exit **Tennenlohe**; direction to Erlangen (B4). Follow the signs "**Universität Südgelände".** After junction **"Technische Fakultät"** please follow the map.

<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"**.

ZAE Bayern Erlangen Abteilung 3

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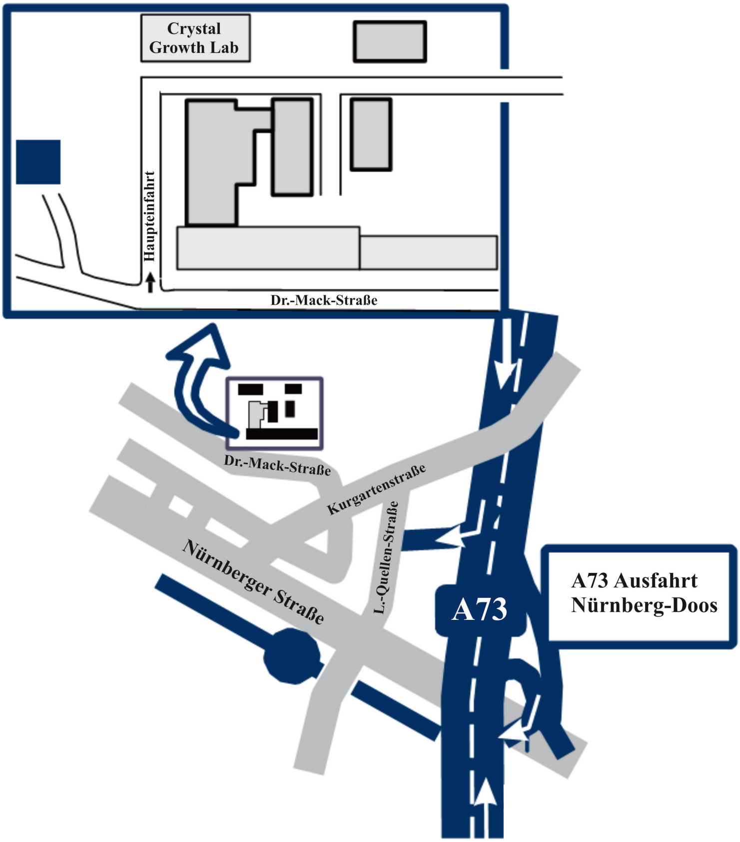
Fax: +49 (0) 9131 / 9398 – 199
E-Mail**:** info3@zae.uni-erlangen.de
Internet: http://www.zae-bayern.de/das-zae-bayern/standorte/erlangen.html

Technikum 2
Crystal Growth Lab
Dr.-Mack-Strasse 77
D-90762 Fürth
Phone: +49 (0) 911 / 65078-65081
FAX: +49 (0) 911 / 65078-65083
Email: crystals@fau.de
Internet: http://crystals.tf.fau.de



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"Auf AEG", Gebäude 16
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Internet: http://www.encn.de