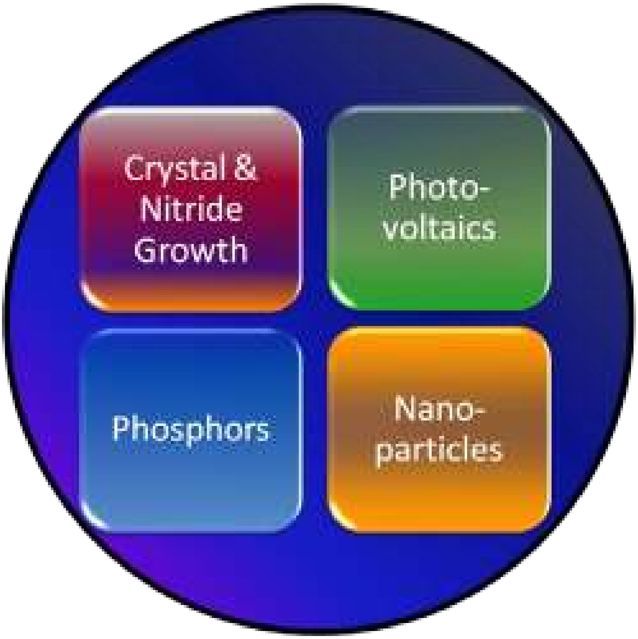
FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG
TECHNISCHE FAKULTÄT

Department of Materials Science and Engineering

i-MEET

Materials for Electronics and Energy Technology



ANNUAL REPORT 2014

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

Lehrstuhl Materialien der Elektronik und der Energietechnologie
Universität Erlangen-Nürnberg
Martensstraße 7
91058 Erlangen

Telefon: +49 (0)9131 85-27633
Fax: +49 (0)9131 85-28495
E-Mail: i-MEET@ww.uni-erlangen.de

Homepage: www.i-meet.ww.fau.de

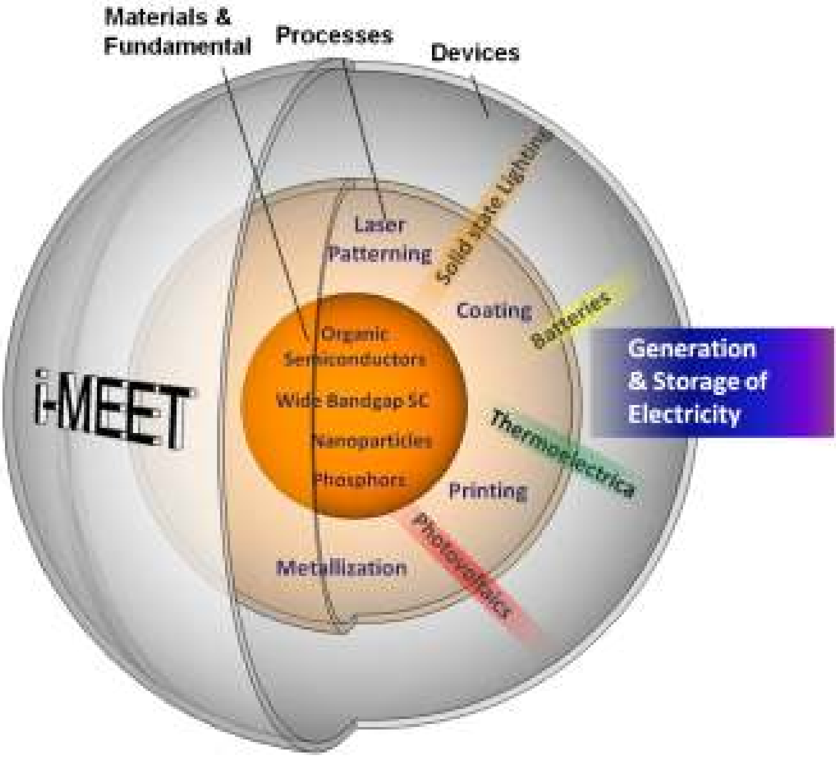
Table of Contents

1. Preface

i-MEET's fifth year was rich and intense in results and work. Our first doctoral candidates in the field of printed photovoltaics graduated with excellent success. I want to explicitly congratulate Tobi Stubhan, Florian Machui, Ning Li, Derya Baran, Peter Kubis and Ivan Litzov to their great achievements and want to thank them for their valuable contributions in building up i-MEET. Michi Woiton and Maik Hessmann graduated with fantastic works at the ZAE, with Michi doing a life demonstration of a self cooled beer barrel to underline the daily importance of nanostructured composites. Felix Oehlschläger, Michl Kaiser and Ulrike Künecke from the Crystal Growth group and Erwin Schmitt from Prof. Winnacker completed our list of 12 doctoral graduations in 2014.
I wish all our absolvents the best for their coming career. Novel semiconductors, energy materials and energy technology have become more relevant than ever, with renewable energies at the forefront of the industrial innovations. Perovskites have rocketed the photovoltaics and semiconductor scene in 2014, for the first time ever demonstrating a low temperature solution processed semiconductor which is polycrystalline and with electronic and optical properties comparable to other inorganic semiconductors. Perovskite and organic semiconductors will dominate our research activities in 2015, where the organic semiconductors are dominating the colorful, flexible and integrated applications while perovskites clearly have the potential to go towards grid connection.

I want to thank all our collaboration and project partners for their great contributions and the pleasant scientific cooperations and all our employees and students for their excellent work, and wish all of us a successfull 2015!

With best regards, Christoph Brabec



(Christoph J. Brabec) (Peter Wellmann) (Wolfgang Heiß)

(Albrecht Winnacker) (Miroslaw Batentschuk)

Erlangen, July 2015

2. Members of the Chair

Head of the chair:

Prof. Dr. Christoph J. Brabec

Secretaries:

Manuela Baumer

Elisabeth Henneberger

Ulrike Knerr

Sandra Wehlmann

Academic administration:

PD Dr. Miroslaw Batentschuk

Professors

Prof. Dr.
Christoph J. Brabec

Prof. Dr.
Wolfgang Heiß

Prof. Dr.-Ing.
Peter Wellmann

Professors emeritus

Prof. Dr. rer. nat.
Georg Müller

Prof. Dr. rer. nat.
Albrecht Winnacker

Associate Professors

Prof. Dr.-Ing.
Matthias Bickermann

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

Marwin Falter

Winfried Habel



Silvan Heilscher

Leonid Kuper

Jonas Mayerhofer

Edeltraud Völkel

Corina Winkler

Ronald Wirth

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

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

Dipl.-Ing. (FH)
Michl Kaiser
Doctoral candidate
i-MEET

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

Dipl.-Ing.
Stefan Möckel
Doctoral candidate
i-MEET

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

Dipl.-Ing.
Felix Oehlschläger
Doctoral candidate
i-MEET

Saskia Schimmel
MSc
Doctoral candidate
i-MEET

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

Dipl.-Ing.
André Zweschke
Doctoral candidate
i-MEET

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

Amir Hashemi
MSc
Doctoral candidate
i-MEET

Dipl.-Ing.
Gordana Jovicic
Postdoc
EnCN

Dr.-Ing.
Michael Woiton
Postdoc
i-MEET

B. Eng.
Sergej Lohvitki
Technician
i-MEET

Organic Photovoltaics (OPV)

(Scientifical staff, doctoral candidates)

Dr.
Tayebeh Ameri
Group leader

Prof. Dr.
Christoph J. Brabec
Group leader

Development of low cost, long lived and highly efficient printed solar cells is the main vision of Organic Photovoltaic (OPV) group. Research in OPV group is focused on development of stable and efficient materials, development of a printed tandem technology, 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 investigated for applications in photovoltaics.

Dr.
Derya Baran
Doct.cand./Postdoc
i-MEET

Dr.
Asli Capan
Postdoc
i-MEET

Dr.
Stefanie Fladischer
Postdoc
i-MEET

Nusret Sena Güldal
MSc (Hons)
Doctoral candidate
i-MEET

Diana Galli
MSc
Doctoral candidate
i-MEET

Nicola Gasperini
MSc
Doctoral candidate
i-MEET

Thomas Heumüller
MSc
Doctoral candidate
i-MEET

Simon Kahmann
MSc
Doctoral candidate
i-MEET


Lili Ke
MSc
Doctoral candidate
i-MEET


Stefan Langner
MSc
Doctoral candidate
i-MEET


Dr.
Ning Li
Doct.cand./Postdoc
i-MEET

Dr. Dipl.-Ing.
Florian Machui
Doct.cand./Postdoc
i-MEET


Jie Min
MSc
Doctoral candidate
i-MEET


Parea Ospina Jose Dario
MSc
Doctoral candidate
i-MEET


Ramirez Quiroz
César Omar, MSc
Doctoral candidate
i-MEET


George Spyropoulos
MSc
Doctoral candidate
i-MEET


Chen Xie
MSc
Doctoral candidate
ZAE


Chaohong Zhang
MSc
Doctoral candidate
i-MEET


Dipl.-Ing.
Hong Zhang
Doctoral candidate
i-MEET

Phosphors & Light (P&L)

(Scientifical staff, doctoral candidates)

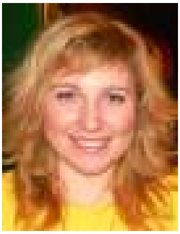
PD Dr.
Miroslaw Batentschuk
Group leader **Phosphors**

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

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

Amjad Ali
MSc
Doctoral candidate
i-MEET

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



Liudmyla Chepyga
MSc
Doctoral candidate
i-MEET

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, and we also combine different techniques for optical modelling. Optical models are verified by experimental measurements before they can be used for numerical optimization.
For each problem, we will choose the most suitable method, i.e. the one that delivers the most accurate results at a reasonable computational effort.

Carina Bronnbauer
MSc
Doctoral candidate
i-MEET

Wei Chen
MSc
Doctoral candidate
i-MEET

Dipl.-Ing.
Fei Guo
Doctoral candidate
i-MEET

Julian Hornich
MSc
Doctoral candidate
i-MEET

Dipl.-Ing.
Johannes Krantz
Doctoral candidate
i-MEET

Dr.
Michael Salvador
Postdoc
i-MEET

Dr. Ing.
Vito Sgobba
Postdoc
i-MEET

Yilei Shen
MSc
Doctoral candidate
i-MEET

Anastasiia Solodovnyk
MSc
Doctoral candidate
ZAE

Processing of Organic Photovoltaics (PPV)

(Scientifical staff, doctoral candidates)

Dr. rer. nat.
Monika Voigt
Group leader

Organic solar cell processing is focused on material and process development for the deposition (printing/ coating), upscaling and patterning of organic solar cells and modules. We develop green formulations for the manufacturing of the solar cells layers, investigate the film formation, the printing and coating parameters (sheet-to-sheet, roll-to-roll) and develop new printing/ coating techniques for transparent/ opaque solar cells and modules. Furthermore we investigate the degradation influences and work on different aspects to improve the lifetime of organic solar cells/ modules.

Dipl.-Phys.
Jens Adams
Doctoral candidate
ZAE

Dipl.-Phys.
Frank Fecher
Doctoral candidate
ZAE

Sarina Keilwitz
MSc
Doctoral candidate
ZAE

Dr. Dipl.-Ing.
Peter Kubis
Doct.cand./Postdoc
i-MEET

Luca Lucera
MSc
Doctoral candidate
ZAE

Dr. Dipl.-Ing.
Florian Machui
Doct.cand./Postdoc
ZAE

Philipp Maisch
MSc
Doctoral candidate
ZAE

Solution Processed Semiconductors for Photovoltaics (IPV)

(Scientifical staff, doctoral candidates)

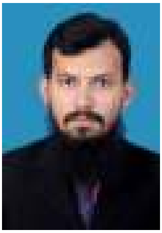
Prof. Dr.
Christoph J. Brabec
Group leader

Dr. (Postdoc)
Hamed Azimi
Group leader

Research in IPV group focuses on the development of low-cost, environmentally friendly and efficient printed solar cells through the use of inorganic and hybrid semiconductors. To reach our goal, we endeavour to unravel the complexity in the synthesis chemistry, dissolution mechanisms, and phase formation of thin films and their relationship to various loss mechanisms in photovoltaic devices. Our focus is on material classes such as chalcopyrites, kesterites and perovskites.

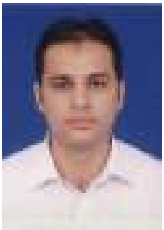
Shi Chen
MEng
Doctoral candidate
i-MEET

Yi Hou
MEng
Doctoral candidate
i-MEET



Laraib Khanzada
MEng
Doctoral candidate
i-MEET

Dr. Dipl.-Chem.
Ivan Litzov
Doct.cand./Postdoc
i-MEET



Atif Makhdoom
MEng
Doctoral candidate
ZAE

Solution Processed Semiconductors Materials (SOPSEM)

(Scientifical staff, doctoral candidates)

Prof. Dr.
Wolfgang Heiß
Group leader

The group is dealing with the synthesis and the research on the fundamental properties of solution processed semiconductor materials. Most of these materials are nanoparticles, capped by ligand molecules and provided in colloidal solutions. The material developments are performed for typical inorganic nanocrystal quantum dots, for organic-inorganic metal-halide perovskites, and for purely organic nanocrystals from hydrogen bonded pigments. Besides the basic optical properties, such as luminescence and photoconductivity also cyclic voltammetry is done to determine oxidation and reduction potentials, as an important input for the application of these materials in future opto-electronic devices. As a result, we have demonstrated in 2014 a post synthetic ligand exchange in $CuSe_2$ nanocrystals to tune their localized surface plasmon resonance, by depositing or withdrawing electrons to/from the nanocrystals. Further, we have demonstrated ultra-sensitive PbS nanocrystal photodetectors, by making use of fully inorganic ligands, and have unraveled the role of trap states in the charge transport process in these devices

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.
This includes steady state and time-resolved techniques.
The steady-state methods covers current/voltage characteristics and spectrally resolved photo-current measurements.
Our setups cover a broad spectral-range from the UV to deep in the IR utilizing a FTIR spectrometer.

For time resolve techniques we perform transient photo-current, photo-voltage, time-of-flight (TOF) and various charge-extraction methods (Charge extraction by linearly increasing voltage (CELIV)).

Thomas Heumüller
MSc
Doctoral candidate
i-MEET

Dipl.-Phys.
Johannes Krantz
Doctoral candidate
i-MEET

Moses Richter
MSc (Hons)
Doctoral candidate
i-MEET

Shreetu Shrestha
MSc
Doctoral candidate
i-MEET

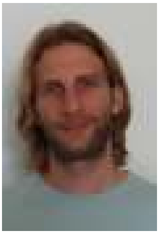
Dr. Dipl.-Phys.
Tobias Stubhan
Doct.cand./Postdoc
i-MEET

Xiaofeng Tang
MSc
Doctoral candidate
i-MEET

Bavarian Center for Applied Energy Research

(ZAE, doctoral candidates, postdocs)


Dipl.-Phys.
Jens Adams


Dipl.-Phys.
Frank Fecher


Dr. Dipl.-Phys.
Maik Heßmann

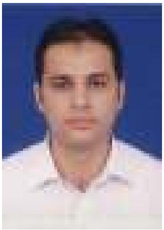

Dipl.-Phys.
Ulrich Hoyer


Sarina Keilwitz
MSc


Da Li
MSc


Luca Lucera
MSc


Philipp Maisch
MSc


Atif Makhdoom
MEng


Anastasiia Solodovnyk
MSc


George Spyropoulos
MSc


Dipl.-Phys.
Arne Riecke


Dipl.-Ing.
Stephan Wittmann


Dr. Dipl.-Ing.
Michael Woiton

External doctoral candidates


Dipl.-Phys.
Carina Ehrig
Siemens


MEng
Tobias Kötter
Siemens


Dipl.-Pys.
Daniel Riedel
Osram


Dipl.-Ing.
Tobias Sauermann
Belectric

Dipl.-Ing
Philipp Schwamb
Osram

Visitors

Dr. Benjamin Lipovsek
Universität Ljubljana, Ljubljana, Slowenia

Prof. Dr. habil. Yuriy Zorenko
Institute of Physics, Kazimierz Wielki University in Bydgoszcz, Poland

3. Bachelor Theses

Ackermann, Alexander (Wellmann)
Entwicklung einer Tiegelbeschichtung für die gerichtete Erstarrung von Silizium für die Photovoltaik

Beck, Felix (Wellmann)
Untersuchung des Germaniumeinbaus in 3C-SiGeC Epitaxieschichten (Investigation of Ge incorporation in 3C-SiGeC epitaxial layers)

Bergmann, Thore (Brabec)
Squaraine-sensitized Ternary Solar Cells based on Poly(3-hexylthiophene-2,5-diyl) (P3HT) and Phenyl-C61-butyric acid methyl ester (PCBM)

Fleissener, Felix (Brabec)
Optimization of P3HT:ICBA Solar Cells based on the Morphology Manipulation and Interface Design

Gall, Thomas (Brabec)
Herstellung organisch-anorganischer Hybridschichten aus Nanopartikel-Dispersionen

Gast, Jessica (Brabec)
Influence of Refractive Indices of Matrix Material and Phosphor Particles on Optical Properties of Down-Shifting Layers

Jena, Daniel (Wellmann)
Entwicklung einer computergestützten Auswertung von in-situ Röntgenaufnahmen zur Bestimmung des Volumens von Nitridkristallen unter ammonothermalen Bedingungen

Joisten, Christoph (Brabec)
Strukturierung von Silberdraht-Elektroden basierend auf Laserablation mit Femtosekundenpulsen

Jordan, Dominik (Brabec)
Solution processed lead-free organic-inorganic halide perovskite solar cells

Kinkelin, Simon-Johannes (Wellmann)
Untersuchung der Defektstruktur und Volumenkristalleigenschaften von 3C-SiC Schichten mittels Tieftemperatur-Photolumineszenz

Korn, Felix (Brabec)
Aufbau, Charakterisierung und Vergleich verschiedener Transformatorkonfigurationen

Küffner, Johannes (Brabec)
Large-scale full-solution, vacuum-free gravure printed ITO-free flexible organic solar cells

Lindner, Michael (Wellmann)
Methodenentwicklung zur Bestimmung der Löslichkeit von GaN unter ammonothermalen Prozessbedingungen mittels in-situ Röntgenabbildung

Müller, Alexander (Wellmann)
Untersuchung der Auflösungskinetik von GaN unter ammonothermalen Prozessbedingungen mittels in-situ Röntgenabbildung

Jonas Müller (Brabec)
Ortsaufgelöste Messungen von Photostrom, Photo- und Elektrolumineszenz an karbazolbasierten und Perowskit-Solarzellen

Raß, Stefan (Batentschuk)
Entwicklung von Synthesemethoden für die Optimierung der Effizienz des $BaAl_2O_4:Eu^{2+}$ *Leuchtstoffs*

Rausch, Sebastian (Wellmann)
Evaluation des räumlichen Auflösungsvermögens während der in situ Röntgen-Computertomographie der Hochtemperatur -Gasphasenzüchtung von Siliziumkarbid

Schmidt, Anja (Wellmann)
Untersuchung der Wachstumsmechanismen während der hydrothermalen Züchtung von Silikat-1-Kristalliten

Schöler, Michael (Wellmann)
Entwicklung eines SiC Lösungszüchtungsprozesses nach dem sogenannten Vertical Bridgman Verfahren

Schorr, Bastian (Brabec)
Entwicklung von Entspiegelungsprozessen

Schreier, Kevin (Brabec)
Systematische Charakterisierung thermischer Kontaktwiderstände an der Stabapparatur

Schröppel, Felix (Wellmann)
Untersuchung der Rückseitenbeschichtung des SiC-Keims für die Optimierung der Einkristallzüchtung

Schwarzenbrunner, Hanna (Wellmann
Gasphasenwachstum von SiC Anlagenelementen für die Anwendung in der ammonothermalen Kristallzüchtung

Steimle, Max (Batentschuk)
Synthesis and characterization of the core-shell $SrAl_2O_4:Eu_2+,RE_3+$ *nanoparticles as nanomarkers in the medicine and the biology*

Vogl, Lilian (Wellmann)
Analyse der Wachstumskinetik beim Aufweiten von Siliziumkarbid durch Auswertung facettierter Kristallbereiche

4. Master Theses

Amin Yousefi AmirAbbas (Brabec)
Solution-based Light Electrochemical Devices with Silver Nanowire Electrodes

Beier, Maximilian (Wellmann)
Entwicklung eines Verfahrens zum Nachchargieren bei der gerichteten Erstarrung von kristallinem Silizium

Boé, Jonas (Brabec)
Interface Modification of High Efficiency Organic Solar Cells

Bundle, Viviane (Batentschuk)
Stabilitätsuntersuchungen an organischen Solarzellen mittles Infrarotspektroskopie

Freund, Raphael (Wellmann)
Untersuchung des facettierten Wachstum von SiC-Kristallen mittels Röntgen-Computertomographie

Hepp, Johannes (Batentschuk)
Contactless detection of unwanted substances in organic solar cells via illuminated lock-in IR-imaging

Hollmann, Andre (Brabec)
Synthesis and characterisation of europium-doped strontium compound nanoparticles for the enhancement of solar cells via luminescent down-shifting layers

Khoram, Parisa (Brabec)
Ternary organic solar cells, using low band-gap polymers and squaraine compounds as sensitizer

Langner, Stefan (Brabec)
Encapsulation, lifetime and degradation measurement of organic solar cells and modules

Leinfelder, Susanne (Wellmann)
Functionalized silicon nanoparticles for combined radiation and gene therapy (Funktionalisierte Silizium Nanopartikel für eine kombinierte Strahlen- und Gen-Therapie)

Pobel, Christoph (Brabec)
Prozessentwicklung für dispersionsverfestigtes Kupfer mittels selektiven Elektronenstrahlschmelzens

Rejek, Tobias (Brabec)
Plasmonic effects of silver nanoparticles in organic semiconductors

Schuh, Philipp (Wellmann)
Growth and charaterization of boron doped 3C-SiC für Solarzellenanwendungen

Schuster, Matthias (Wellmann)
Herstellung und Charakterisierung einer $CuInSe_2$ *Solarzelle mit verdruckbarer, transparenter Frontelektrode*

Wernicke, Tobias (Wellmann)
Herstellung und Charakterisierung einer voll verdruckbaren $CuInSe_2$ *Solarzellen-Absorberschicht auf Basis von CuIn- und Se-Nanopartikeln*

5. Doctoral Theses

Doctoral Theses in Preparation

Adams, Jens (Brabec, ZAE)
Failure analysis and long term stability of thin film solar cells and modules

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

Bachmann, Jonas (Brabec, i-MEET)
Organic polymer solar modules characterized by thermal methods

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

Chen, Wei (Brabec, i-MEET)
Inorganic / Organic light conversion composites for PV applications

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

Ehrig, Carina Miriam (Brabec, external)
Magnesium Silicides for Optoelectronic Devices

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

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

Galli, Diana (Brabec, i-MEET)
Near IR sensitization of polymer / fullerene solar cells

Gasparini, Nicola (Brabec, i-MEET)
Processing and characterization of small molecule type NIR sensitized BHJ solar cells / modules

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

Guo, Fei (Brabec, i-MEET)
Semitransparent organic solar cells

Heumüller, Thomas (Brabec, i-MEET)
Structure property correlation of microstructure modifications in semiconducting heterojunction composites

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)
Synthesis & characterization of novel Phthalocyanine based small molecules

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

Krantz, Johannes (Brabec, i-MEET)
Solution processed metallic nanorod electrodes as ITO replacement for thin film solar cells

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

Levchuk, Ievgen (Batentschuk, i-MEET)
Entwicklung und Optimierung von nanokristallinen Leuchtstoffen für Lichtkonverionsschichten in Solarzellen

Li, Da (Brabec, ZAE)
Surface passivation of thin film silicon

Lucera, Luca (Brabec, ZAE)
Coating and printing technologies for thin film solar cells

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

Min, Jie (Brabec, i-MEET)
Design & fabrication of OPVs based on solution-processed small molecules

Möckel, Stefan (Wellmann, i-MEET)
Kristallisationsmechanismen nanopartikulärer Metall-Chalkogen-Kompositschichten zur Herstellung Chalkopyrit-Absorberschichten für die Dünnschichtphotovoltaik

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

Riedel, Daniel (Brabec, external)
Internal light extraction in organic light emitting devices

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

Schwamb, Philipp (Brabec, external)
Flexible white OLEDs

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

Solodovnyk, Anastasiia (Brabec, ZAE)
Films with Particle Filled Systems for Solar Cell Applications

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

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

22.01.2014
Stubhan Tobias (Brabec, i-MEET)
Controlling the Electronic Interface Properties in Polymer-fullerene Bulk-heterojunction Solar Cells // Steuerung der elektronischen Kontakteigenschaften in organischen Polymer-Fulleren Solarzellen

07.04.2014
Oehlschläger, Felix (Wellmann, i-MEET)
Untersuchung von Halbleiterschichten mittels optischer Spektroskopie

04.06.2014
Machui Florian (Brabec, i-MEET)
Formulation of Semiconductor Solutions for Organic Photovoltaic Devices / Formulierung von Halbleiterlösungen für die organische Photovoltaik

13.06.2014
Kaiser Michl (Wellmann, i-MEET)
Herstellung von polykristallinen SiC-Quellenmaterialien und ihre Anwendung bei der Sublimationsepitaxie von einkristallinem 3C-SiC

10.07.2014
Li Ning (Brabec, i-MEET)
Hybrid Heterojunction Recombination Layers for Printed Organic Tandem Solar Cells / Hybride Halbleiterkomposite als Rekombinationsschichten für gedruckte Tandemzellen

16.07.2014
Woiton, Michael (Brabec, i-MEET)
Netzartig strukturierte Oberflächen aus präkeramischen Polymeren

29.07.2014
Schmitt Erwin (Winnacker, i-MEET)
Untersuchungen zur Defektentstehung bei der Gasphasenzüchtung von Siliziumkarbid-Einkristallen

30.09.2014
Heßmann, Thomas Maik (Brabec, i-MEET)
Laser Welding of Silicon Foils for Thin-Film Solar Cell Manufacturing / Laserschweißen von Siliziumfolien zur Herstellung von Dünnschicht-Solarzellen

28.10.2014
Baran Derya (Brabec, i-MEET)
Smart Concepts for Mapping Optoelectronic Properties of Organic Solar Cells: Strategies for Fast and Contactless Material Optimization
Intelligente Konzepte für das Mapping der optoelektronischen Eigenschaften von organischen Solarzellen: Strategien für schnelle und kontaktlose Materialoptimierung

10.11.2014
Künecke Ulrike (Wellmann, i-MEET)
Charakterisierung von Inhomogenitäten an CIGSSe-Solarzellenabsorbern im Rasterelektronenmikroskop

13.11.2014
Kubis Peter (Brabec, i-MEET)
Design and Development of Ultra-fast Laser Patterning Processes for the Production of Organic Photovoltaic Modules with High Geometric Fill Factor
Entwicklung von ultraschnellen Laser-Produktionsprozessen für die Herstellung von organischen Solarmodulen mit hohem geometrischen Füllfaktor

17.12.2014
Litzov Ivan (Brabec, i-MEET)
Design, Synthesen und Charakterisierung von n-Typ-Metalloxidhalbleitern als Interfacematerialien für (opto)-elektronische Bauelemente

6. Awards

Baran Derya
Presentation Award of EAM (Engineering of Advanced Materials) Young Researchers' Day 17 February 2014, Fraunhofer IISB Erlangen, Germany
Flash Talk: *An Elegant Method to Anticipate the Potential Efficiency of Solar Cells without Device Fabrication*

Li Ning
Chinese Government Award for Outstanding Self-financed Students AbroadThe award was founded by the Chinese government with the purpose of rewarding the academic excellence of self-financed Chinese students studying overseas.

7. Publications (Full Papers and Conference Proceedings)

Full Papers

J. Adams, A. Vetter, F. Hoga, F. Fecher, J.P. Theisen, C.J. Brabec, C. Buerhop-Lutz
The influence of defects on the cellular open circuit voltage in $CuInGaSe_2$ thin film solar modules - An illuminated lock-in thermography study
Solar Energy Materials and Solar Cells ***123****, pp. 159-165, 2014*

Tayebeh Ameri, Parisa Khoram, Thomas Heumüller, Derya Baran, Florian Machui, Anna Troeger, Vito Sgobba, Dirk M. Guldi, Marcus Halik, Silke Rathgeber, Ullrich Scherff and Christoph J. Brabec
Morphology analysis of near IR sensitized polymer/fullerene organic solar cells by implementing low bandgap heteroanalogue C-/Si-PCPDTBT
Journal of Materials Chemistry A ***2 (45)****, pp. 19461-19472, 2014*

Thomas R. Andersen, Henrik F. Dam, Markus Hösel, Martin Helgesen, Jon E. Carlé, Thue T. Larsen-Olsen, Suren A. Gevorgyan, Jens W. Andreasen, Jens Adams, Ning Li, Florian Machui, George D. Spyropoulos, Tayebeh Ameri, Noella Lemaitre, Mathilde Legros, Arnulf Scheel, Detlef Gaiser, Kilian Kreul, Stephane Berny, Owen R. Lozman, Sirpa Nordman, Marja Välimäki, Marja Vilkman, Roar. R. Søndergaard, Mikkel Jørgensen, Christoph J. Brabec and Frederik C. Krebs
Scalable, ambient atmosphere roll-to-roll manufacture of encapsulated large area, flexible organic tandem solar cell modules
Energy and Environmental Science ***7 (9)****, pp. 2925-2933, 2014*

Azimi, H., Hou, Y., Brabec, C.J.
Towards low-cost, environmentally friendly printed chalcopyrite and kesterite solar cells
Energy and Environmental Science ***7 (6)****, pp. 1829-1849, 2014*

Hamed Azimi, Susanne Kuhri, Andres Osvet, Gebhard Matt, Laraib S. Khanzada, Mario Lemmer, Norman A. Luechinger, Mats I. Larsson, Eitan Zeira, Dirk M. Guldi and Christoph J. Brabec
Effective Ligand Passivation of Cu_2O Nanoparticles through Solid-State Treatment with Mercaptopropionic Acid
Journal of the American Chemical Society ***136 (20)****, pp. 7233-7236, 2014*

Derya Baran, Ning Li, Anne-Catherine Breton, Andres Osvet, Tayebeh Ameri, Mario Leclerc, and Christoph J. Brabec
Qualitative Analysis of Bulk-Heterojunction Solar Cells without Device Fabrication: An Elegant and Contactless Method
Journal of the American Chemical Society ***136 (31)****, pp. 10949-1095, 2014*

S. Besold, U. Hoyer, J. Bachmann, T. Swonke, P. Schilinsky, R. Steim, C.J. Brabec
Quantitative imaging of shunts in organic photovoltaic modules using lock-in thermography
*Solar Energy Materials and Solar Cells **124**, pp. 133-137, 2014*

Ignasi Burgués-Ceballos, Florian Machui, Jie Min, Tayebeh Ameri, Monika M. Voigt, Yuriy N. Luponosov, Sergei A. Ponomarenko, Paul D. Lacharmoise, Mariano Campoy-Quiles, and Christoph J. Brabec
Solubility Based Identification of Green Solvents for Small Molecule Organic Solar Cells
*Advanced Functional Materials **24 (10)**, pp. 1449-1457, 2014*

Haluk Dinçalp, Oguzhan Çimen, Tayebeh Ameri, Christoph J. Brabec, Sıddık Içli
Synthesis, characterization and optoelectronic properties of a new perylene diimide-benzimidazole type solar light harvesting dye
*Spectrochimica Acta - Part A: Molecular and Biomolecular Spectroscopy **128**, pp. 197-206, 2014*

Ikerne Etxebarria, AliceFurlan, JonAjuria, FrankW.Fecher, MonikaVoigt, Christoph J.Brabec, MartijnM.Wienk, LennekeSlooff, SjoerdVeenstra, Jan Gilot, RobertoPacios
Series vs parallel connected organic tandem solar cells: Cell performance and impact on the design and operation of functional modules
*Solar Energy Materials and Solar Cells **130**, pp. 495-504, 2014*

Frank W. Fecher, Alexander Pérez Romero, Christoph J. Brabec, Claudia Buerhop-Lutz
Influence of a shunt on the electrical behavior in thin film photovoltaic modules – A 2D finite element simulation study
*Solar Energy **105**, pp. 494-504, 2014*

Fei Guo, Peter Kubis, Tobias Stubhan, Ning Li, Derya Baran, Thomas Przybilla, Erdmann Spiecker, Karen Forberich, and Christoph J. Brabec
Fully Solution-Processing Route toward Highly Transparent Polymer Solar Cells
*ACS Applied Materials and Interfaces **6 (20)**, pp. 18251-18257, 2014*

Fei Guo, Peter Kubis, Ning Li, Thomas Przybilla, Gebhard Matt, Tobias Stubhan, Tayebeh Ameri, Benjamin Butz, Erdmann Spiecker, Karen Forberich, and Christoph J. Brabec
Solution-Processed Parallel Tandem Polymer Solar Cells Using Silver Nanowires as Intermediate Electrode
*ACS Nano **8 (12)**, pp. 12632-12640, 2014*

Thomas Heumueller, William R. Mateker, I. T. Sachs-Quintana, Koen Vandewal, Jonathan A. Bartelt, Timothy M. Burke, Tayebeh Ameri, Christoph J. Brabec and Michael D. McGehee
Reducing burn-in voltage loss in polymer solar cells by increasing the polymer crystallinity
*Energy and Environmental Science **7 (9)**, pp. 2974-2980, 2014*

Peter Kubis, Luca Lucera, Florian Machui, George Spyropoulos, Johann Cordero, Alfred Frey, Joachim Kaschta, Monika M. Voigt, Gebhard J. Matt, Eitan Zeira, Christoph J. Brabec
High precision processing of flexible P3HT/PCBM modules with geometric fill factor over 95%
Organic Electronics: physics, materials, application ***15 (10)****, pp. 2256-2263, 2014*

Ning Li, Derya Baran, George D. Spyropoulos, Hong Zhang, Stephane Berny, Mathieu Turbiez, Tayebeh Ameri, Frederik C. Krebs, and Christoph J. Brabec
Environmentally Printing Efficient Organic Tandem Solar Cells with High Fill Factors: A Guideline Towards 20% Power Conversion Efficiency
Advanced Energy Materials ***4 (11)****, art. no. 1400084, 2014*

Ning Li, PeterKubis, Karen Forberich, Tayebeh Ameri, Frederik C.Krebs, Christoph J.Brabec
Towards large-scale production of solution-processed organic tandem modules based on ternary composites: Design of the intermediate layer, device optimization and laser based module processing
Solar Energy Materials and Solar Cells ***120 (PART B)****, pp. 701-708, 2014*

Ning Li, Tobias Stubhan, Johannes Krantz, Florian Machui, Mathieu Turbiez, Tayebeh Ameri and Christoph J. Brabec
A universal method to form the equivalent ohmic contact for efficient solution-processed organic tandem solar cells
Journal of Materials Chemistry A ***2 (36)****, pp. 14896-14902, 2014*

Ivan Litzov, Hamed Azimi, Gebhard Matt, Peter Kubis, Tobias Stubhan, Georgi Popov, Christoph J. Brabec
Accelerated degradation of Al^{3+} doped ZnO thin films using damp heat test
Organic Electronics: physics, materials, applications ***15 (2)****, pp. 569-576, 2014*

Yuriy N. Luponosov, Jie Min, Tayebeh Ameri, Christoph J. Brabec, Sergei A. Ponomarenko
A new dithienosilole-based oligothiophene with methyldicyanovinyl groups for high performance solution-processed organic solar cells
Organic Electronics: physics, materials, applications ***15 (12)****, pp. 3800-3804, 2014*

Florian Machui, Markus Hösel, Ning Li, George D. Spyropoulos, Tayebeh Ameri, Roar R. Søndergaard, Mikkel Jørgensen, Arnulf Scheel, Detlef Gaiser, Kilian Kreul, Daniel Lenssen, Mathilde Legros, Noella Lemaitre, Marja Vilkman, Marja Välimäki, Sirpa Nordman, Christoph J. Brabec and Frederik C. Krebs
Cost analysis of roll-to-roll fabricated ITO free single and tandem organic solar modules based on data from manufacture
Energy and Environmental Science ***7 (9)****, pp. 2792-2802, 2014*

Florian Machui, Luca Lucera, George D. Spyropoulos, Johann Cordero, Abid S. Ali, Peter Kubis, Tayebeh Ameri, Monika M. Voigt, Christoph J. Brabec
Large area slot-die coated organic solar cells on flexible substrates with non-halogenated solution formulations
Solar Energy Materials and Solar Cells ***128****, pp. 441-446, 2014*

Jie Min, Yuriy N. Luponosov, Alexander N. Solodukhin, Nina Kausch-Busies, Sergei A. Ponomarenko, Tayebeh Ameri and Christoph J. Brabec
A star-shaped D-π-A small molecule based on a tris(2-methoxyphenyl)amine core for highly efficient solution-processed organic solar cells
Journal of Materials Chemistry C, ***2 (36)****, pp. 7614-7620, 2014*

Jie Min, Yuriy N. Luponosov, Andreas Gerl, Marina S. Polinskaya, Svetlana M. Peregudova, Petr V. Dmitryakov, Artem V. Bakirov, Maxim A. Shcherbina, Sergei N. Chvalun, Souren Grigorian, Nina Kaush-Busies, Sergei A. Ponomarenko,Tayebeh Ameri, and Christoph J. Brabec
Alkyl chain engineering of solution-processable star-shaped molecules for high-performance organic solar cells
Advanced Energy Materials ***4 (5)****, art. no. 1301234, 2014*

Jie Min,Yuriy N. Luponosov, Derya Baran, Sergei N. Chvalun, Maxim A. Shcherbina, Artem V. Bakirov, Petr V. Dmitryakov, Svetlana M. Peregudova, Nina Kausch-Busies, Sergei A. Ponomarenko, Tayebeh Ameri and Christoph J. Brabec
Effects of oligothiophene π-bridge length on physical and photovoltaic properties of star-shaped molecules for bulk heterojunction solar cells
Journal of Materials Chemistry A ***2 (38)****, pp. 16135-16147, 2014*

Jie Min, Yuriy N. Luponosov, Zhi-Guo Zhang, Sergei A. Ponomarenko, Tayebeh Ameri, Yongfang Li , and Christoph J. Brabec
Interface Design to Improve the Performance and Stability of Solution-Processed Small-Molecule Conventional Solar Cells
Advanced Energy Materials ***4 (16)****, 2014*

Haiyan Ou,Yiyu Ou, Aikaterini Argyraki, Saskia Schimmel, Michl Kaiser, Peter Wellmann, Margareta K. Linnarsson, Valdas Jokubavicius, Jianwu Sun, Rickard Liljedahl, and Mikael Syväjärvi
Advances in wide bandgap SiC for optoelectronics
The European Physical Journal B ***87:58****, pages 16, 2014*

S. A. Ponomarenko, Y. N. Luponosov, J. Min, A. N. Solodukhin, N. M. Surin, M. A. Shcherbina, S. N. Chvalun, T. Ameri and C. Brabec
Design of donor-acceptor star-shaped oligomers for efficient solution-processible organic photovoltaics
Faraday Discussions ***174****, pp. 313-339, 2014*

I. T. Sachs-Quintana, Thomas Heumüller, William R. Mateker, Darian E. Orozco, Rongrong Cheacharoen, Sean Sweetnam, Christoph J. Brabec, and Michael D. McGehee
Electron Barrier Formation at the Organic-Back Contact Interface is the First Step in Thermal Degradation of Polymer Solar Cells
Advanced Functional Materials ***24 (25)****, pp. 3978-3985, 2014*

Saskia Schimmel, Ulrike Künecke, Hasan Baser, Thomas G. Steigerwald, Benjamin Hertweck, Nicolas S. A. Alt, Eberhard Schlücker, Wilhelm Schwieger, and Peter Wellmann
Towards X-ray in-situ visualization of ammonothermal crystal growth of nitrides
Phys. Status Solidi C ***11, No. 9****, 1439–1442, 2014*

G. D. Spyropoulos, P. Kubis, N. Li, D. Baran, L. Lucera, M. Salvador, T. Ameri, M. M. Voigt, F. C. Krebs and C. J. Brabec
Flexible organic tandem solar modules with 6% efficiency: Combining roll-to-roll compatible processing with high geometric fill factors
Energy and Environmental Science ***7 (10)****, pp. 3284-3290, 2014*

Koen Vandewal, Johannes Widmer, Thomas Heumueller, Christoph J. Brabec, Michael D. McGehee, Karl Leo, Moritz Riede, and Alberto Salleo
Increased Open-Circuit Voltage of Organic Solar Cells by Reduced Donor-Acceptor Interface Area
Advanced Materials ***26 (23)****, pp. 3839-3843, 2014*

Xiao Wang, Hans-Joachim Egelhaaf, Hans-Georg Mack, Hamed Azimi, Christoph J. Brabec, Alfred J. Meixner, and Dai Zhang
Morphology Related Photodegradation of Low-Band-Gap Polymer Blends
Advanced Energy Materials ***4 (17)****, art. no. 1400497, 2014*

Rachmat Adhi Wibowo, Stefan Moeckel, Hyesun Yoo, Astrid Hoelzing, Rainer Hock, Peter J. Wellmann
Formation of Cu_2SnSe_3 from stacked elemental layers investigated by combined in situ X-ray diffraction and differential scanning calorimetry techniques
Journal of Alloys and Compounds ***588****, pp. 254–258, 2014*

N. Wolf, T. Stubhan, J.Manara, V. Dyakonov, C.J. Brabec, N. Wolf, T. Stubhan, J. Manara, V. Dyakonov, C.J. Brabec
Stabilization of aluminum doped zinc oxide nanoparticle suspensions and their application in organic solar cells
Thin Solid Films ***564****, pp. 213-217, 2014*

Hong Zhang, Hamed Azimi, Yi Hou, Tayebeh Ameri, Thomas Przybilla, Erdmann Spiecker, Mario Kraft, Ullrich Scherf, and Christoph J. Brabec
Improved High-Efficiency Perovskite Planar Heterojunction Solar Cells via Incorporation of a Polyelectrolyte Interlayer
Chemistry of Materials ***26****, pp. 5190-5193, 2014*

Hong Zhang, Tobias Stubhan, Ning Li, Mathieu Turbiez, Gebhard J. Matt, Tayebeh Ameri and Christoph J. Brabec
A solution-processed barium hydroxide modified aluminum doped zinc oxide layer for highly efficient inverted organic solar cells
*Journal of Materials Chemistry A **2 (44)**, pp. 18917-18923, 2014*

Yu. Zorenko, V. Gorbenko, T. Zorenko, V. Savchyn, M. Batentschuk, A. Osvet, C. Brabec
Luminescent properties and energy transfer processes in YAG:Er single crystalline films
*Journal of Luminescence **154**, pp. 198-203, 2014*

Solar Energy Materials & Solar Cells 123 (2014) 159–165

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

The influence of defects on the cellular open circuit voltage in $CuInGaSe_2$ thin film solar modules—An illuminated lock-in thermography study

J. Adams [a,*], A. Vetter [a], F. Hoga [a], F. Fecher [a], J.P. Theisen [b], C.J. Brabec [a,c], C. Buerhop-Lutz [a]

[a] Bavarian Center for Applied Energy Research (ZAE Bayern), Haberstraße 2a, 91058 Erlangen, Germany
[b] Manz CIGS Technology GmbH, Alfred Leikam-Str. 25, 74523 Schwäbisch Hall, Germany
[c] Institute of Materials for Electronics and Energy (i-MEET), Friedrich-Alexander University Erlangen-Nürnberg, Martensstraße 7, 91058 Erlangen, Germany

ARTICLE INFO

Article history:
Received 8 May 2013
Received in revised form
22 November 2013
Accepted 4 January 2014
Available online 1 February 2014

Keywords:
ILIT
Cell voltage
Open circuit
V_{oc}
Defect
Lock-in thermography

ABSTRACT

$CuInGaSe_2$ (CIGS) thin film solar modules, despite their high efficiency, may contain three different kinds of macroscopic defects referred to as bulk defects, interface defects and interconnect defects. This occurs due to film's sensitivity to inhomogeneities during the manufacturing process. The result is a decrease of electrical power output from a cell or module. In this paper, we present the influence of macroscopic defects on the electrical behavior of CIGS thin film solar cells. To accomplish this, we investigated the relation between the IR-signal emitted of a defect in a cell (measured using illuminated lock-in thermography ILIT) and the respective open circuit cell voltage ($V_{oc,cell}$) under low light conditions (≈ 100 W/m²). Furthermore, we developed a modified masking method of measuring $V_{oc,cell}$ of a single cell within a thin film solar module.

1. Introduction

Since their inception, solar cells and modules based on $CuInGaSe_2$ (CIGS) have been successfully developed into high performance solar energy converters. Electrical efficiencies of over 20% for cells, 17% for submodules and 15% for conventional thin film solar modules indicate that CIGS is a promising candidate for thin film solar technology [1,2]. During the successive steps of the manufacturing process, macroscopic defects, in particular bulk defects, interface defects, and interconnect defects could be possibly introduced to the cell. The end result is that defects cause a decrease in the cells electrical output. The amount of this decrease depends predominantly on the defect type and size as well as the illumination conditions. At low light illumination (≈ 100 W/m²) even "weak" defects may lead to a pronounced loss of electrical cell output [3].

In order to improve the high efficiency of these devices, it is crucial to have a firm physical and electrical understanding of macroscopic defects and their origins. In particular, a quantitative description of the influence of a defect on the cell and module performance is essential. Different imaging techniques such as electroluminescence (EL), photoluminescence (PL), dark lock-in thermography (DLIT), and illuminated lock-in thermography (ILIT) have been utilized as powerful tools for characterizing the loss processes in both solar cells and modules [4–8]. DLIT has been used intensively in order to locate increased local power dissipation. This is accomplished by measuring small surface temperature differences using a high spatial and thermal resolution infrared (IR) camera [9]. DLIT measurements periodically excite the cell or module with an electrical current or voltage. The IR camera then detects the IR-emission by the excited sample. Specialized software is used to match this signal with two periodic weighting functions in order to minimize the noise signal. Due to the lock-in principle, even defects with a weak influence on the electrical cell parameters (such as open circuit voltage, V_{oc}) can be detected [6,9–11]. A modification of this method, ILIT, was first introduced by Isenberg et al. [5,12] and by Kaes et al. [13]. Using this method, a sample (silicon solar cell) is excited by pulsed light. Under the V_{oc}-condition (the solar cell or module is not externally connected), ILIT is a fast, contact-less, and non-destructive method allowing the detection of a large variety of power loss processes under real operating conditions. Recently, this method was published as a fast quality control tool for CIGS modules [14].

In this paper, we will present a relationship between the IR-emission of a defect in a cell and the corresponding cellular open circuit voltage ($V_{oc,cell}$). We developed a modified masking

---

* Corresponding author.
E-mail address: jens.adams@zae.uni-erlangen.de (J. Adams).

0927-0248/$ - see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.solmat.2014.01.014

Journal of
Materials Chemistry A

PAPER

View Article Online
View Journal | View Issue

Cite this: J. Mater. Chem. A, 2014, 2, 19461

Morphology analysis of near IR sensitized polymer/fullerene organic solar cells by implementing low bandgap heteroanalogue C-/Si-PCPDTBT†

Tayebeh Ameri,*[a] Parisa Khoram,[a] Thomas Heumüller,[a] Derya Baran,[a] Florian Machui,[a] Anna Troeger,[c] Vito Sgobba,[c] Dirk M. Guldi,[c] Marcus Halik,[d] Silke Rathgeber,[e] Ullrich Scherf[f] and Christoph J. Brabec[ab]

Received 7th August 2014
Accepted 15th September 2014

DOI: 10.1039/c4ta04070h

www.rsc.org/MaterialsA

In the current work, we have investigated the morphological aspects of the ternary solar cells based on host matrices of P3HT:PCBM and P3HT:ICBA, using the low bandgap polymer analogues of C- and Si-bridged PCPDTBT as near IR sensitizers, which show noticeably different performance. A direct comparison of these well-functional and poorly functional ternary blend systems provides insights into the bottlenecks of device performance and enables us to set up an initial set of design rules for ternary organic solar cells. Our study reveals the importance of surface energy as a driving force controlling sensitizer location and morphology formation of ternary blends. The interfacial surface energy results indicate that Si-PCPDTBT locates at amorphous interfaces and P3HT crystallites, while C-PCPDTBT tends to accumulate at amorphous interfaces and semi-crystalline (or agglomerated) domains of the fullerene derivatives. GIWAXS and SCLC results support this prediction where adding high content of C-PCPDTBT influences mainly the semi-crystallinity (aggregation) of the fullerene and reduces the electron mobility, but Si-PCPDTBT impacts mainly the P3HT ordering and, in turn, deteriorates the hole mobility. These findings show that the disruption of the fullerene semi-crystalline domains is more detrimental to the device performance than the disruption of the polymer domains.

1. Introduction

Recently, great efforts have been directed towards developing organic solar cells (OSCs) with improved power conversion efficiencies, leading to improved performance by over 10%.[1–4] The entrance of organic photovoltaics into the niche market, indeed, indicates the huge potential of this technology. Further developments are, however, necessary to make organic photovoltaics an investment-worthy energy production technology.[5,6] Recently, the concept of ternary bulk-heterojunction solar cells has evolved as an alternative to extend the narrow absorption window of large bandgap polymers into the near IR regions.[7] This approach provides an alternative to achieve high efficiency and cost-effective organic photovoltaics avoiding all intricacies of multi-junction organic solar cells, although it would not tackle the detailed balance limit.[8,9] In 2010, Koppe *et al.*[10] confirmed for the first time the concept of near IR sensitization of organic solar cells based on a blend of poly(3-hexylthiophene) (P3HT) and [6,6]-phenyl-C_{61}-butyric acid methyl ester (PCBM) by adding the low bandgap poly[2,6-(4,4-bis-(2-ethylhexyl)-4*H*-cyclopenta[2,1-*b*;3,4-*b*′]-dithiophene)-*alt*-4,7-(2,1,3-benzothiadiazole)] (C-PCPDTBT)[10,11] as a sensitizer. Later on, using its Si-bridged analogue, that is, 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),[12,13] as a sensitizer for P3HT:PCBM, we documented an even higher potential of the near IR sensitization concept.[14] Interestingly, these two similar low bandgap polymers revealed completely different functionality in the ternary devices. Please note that both of these polymers were implemented just as sensitizers without an active role to play in the transport of the free charge carriers.[10,15]

---

[a] Institute of Materials for Electronics and Energy Technology (i-MEET), Department of Materials Science and Engineering, Friedrich-Alexander University Erlangen-Nuremberg, Martensstrasse 7, 91058 Erlangen, Germany. E-mail: tayebeh.ameri@fau.de

[b] Bavarian Center for Applied Energy Research (ZAE Bayern), Haberstr. 2a, 91058 Erlangen, Germany

[c] Department of Chemistry and Pharmacy & Interdisciplinary Center for Molecular Materials, Friedrich-Alexander University Erlangen-Nuremberg, Egerlandstrasse 3, 91058 Erlangen, Germany

[d] Organic Materials and Devices (OMD), Institute of Polymer Materials, Friedrich-Alexander-University of Erlangen-Nuremberg, Martensstraße 7, 91058 Erlangen, Germany

[e] Institute for Natural Sciences, Physics Department, University of Koblenz-Landau, Universitätsstraße 1, 56070 Koblenz, Germany

[f] FB C – Mathematik & Naturwissenschaften Fachgebiet Makromolekulare Chemie & Institut für Polymertechnologie, Bergische Universität Wuppertal, Gaußstraße 20, 42097 Wuppertal, Germany

† Electronic supplementary information (ESI) available. See DOI: 10.1039/c4ta04070h

Energy & Environmental Science

COMMUNICATION

View Article Online
View Journal | View Issue

Scalable, ambient atmosphere roll-to-roll manufacture of encapsulated large area, flexible organic tandem solar cell modules

Cite this: Energy Environ. Sci., 2014, 7, 2925

Received 17th April 2014
Accepted 12th May 2014

DOI: 10.1039/c4ee01223b

www.rsc.org/ees

Thomas R. Andersen,[a] Henrik F. Dam,[a] Markus Hösel,[a] Martin Helgesen,[a] Jon E. Carlé,[a] Thue T. Larsen-Olsen,[a] Suren A. Gevorgyan,[a] Jens W. Andreasen,[a] Jens Adams,[bc] Ning Li,[bc] Florian Machui,[bc] George D. Spyropoulos,[bc] Tayebeh Ameri,[bc] Noëlla Lemaître,[d] Mathilde Legros,[d] Arnulf Scheel,[e] Detlef Gaiser,[f] Kilian Kreul,[f] Stephane Berny,[g] Owen R. Lozman,[g] Sirpa Nordman,[h] Marja Välimäki,[h] Marja Vilkman,[h] Roar R. Søndergaard,[a] Mikkel Jørgensen,[a] Christoph J. Brabec[bc] and Frederik C. Krebs*[a]

Inline printing and coating methods have been demonstrated to enable a high technical yield of fully roll-to-roll processed polymer tandem solar cell modules. We demonstrate generality by employing different material sets and also describe how the ink systems must be carefully co-developed in order to reach the ambitious objective of a fully printed and coated 14-layer flexible tandem solar cell stack. The roll-to-roll methodologies involved are flexographic printing, rotary screen printing, slot-die coating, X-ray scattering, electrical testing and UV-lamination. Their combination enables the manufacture of completely functional devices in exceptionally high yields. Critical to the ink and process development is a carefully chosen technology transfer to industry method where first a roll coater is employed enabling contactless stack build up, followed by a small roll-to-roll coater fitted to an X-ray machine enabling *in situ* studies of wet ink deposition and drying mechanisms, ultimately elucidating how a robust inline processed recombination layer is key to a high technical yield. Finally, the transfer to full roll-to-roll processing is demonstrated.

Broader context

The polymer solar cell is one of the most scientifically reported energy technologies not only due to the promises of being an exceptionally low environmental impact technology on a massive scale, but also because it can be realized in a myriad of ways and can be made subject to a near infinite level of variation. The enormous complexity is reflected both in the ease with which they can be made and also in the difficulty with which they are made efficient. In spite of the enormous number of reports (>10 000) there is still no standard procedure for realizing high efficiency devices beyond single unit cells. Efforts in scaling such that generic methods are available is key to reaching this level and significant research is needed within this area if the technology is to become viable outside academia. The highest efficiency for the polymer solar cell is possible through the multi-junction architecture where two or more junctions are stacked on top of each other, thus representing a task that is both difficult and challenging, but also potentially rewarding if it can be realized. We show how fully scalable tandem OPV modules can be prepared using full roll-to-roll processing and we also illustrate what equipment is needed to carry out the experiments and highlight areas that could facilitate further development of the technology, especially with respect to materials development and materials properties.

1. Introduction

The pinnacle of complexity for fully solution-processed organic electronics is represented by the organic tandem solar cell[1] that requires a large selection of materials, careful formulation into inks and solvent systems compatible with the required combination of fast printing/coating techniques that are included in the process along with challenging film thickness and quality control. The motivation is clearly the desire to tap into the potentially higher power conversion efficiency that multi-junction solar cells have to offer. At the same time it is assumed that the added complexity that multi-junction solar cells also imply can be overcome easily. The power conversion efficiency of laboratory-scale polymer tandem solar cell devices reportedly exceeds 10% (ref. 2 and 3) and has been predicted to have technical potential in the range of 15–25%.[4,5] The scaled efficiency that can currently be reached with fully roll-to-roll processed single junction polymer solar cells, that are true to the art and vision of high speed manufacture without any discrete steps, is significantly lower than the record single junction

---

[a] Department of Energy Conversion and Storage, Technical University of Denmark, Frederiksborgvej 399, DK-4000 Roskilde, Denmark. E-mail: frkr@dtu.dk
[b] i-MEET (Institute Materials for Electronics and Energy Technology), Friedrich-Alexander University Erlangen-Nürnberg, Martensstrasse 7, D-91058 Erlangen, Germany
[c] Bavarian Center for Applied Energy Research, Center for Renewable Energies, Haberstrasse 2a, D-91058 Erlangen, Germany
[d] CEA, LITEN, INES Campus, F-73375 Le Bourget du Lac, France
[e] Heraeus Precious Metals GmbH & Co. KG, Electronic Materials Division, Chempark Leverkusen Bldg. B202, 51368 Leverkusen, Germany
[f] DELO Industrial Adhesives, DELO-Allee 1, 86949 Windach, Germany
[g] Merck Chemicals Ltd., Chilworth Technical Centre, University Parkway, Southampton, SO16 7QD, UK
[h] VTT Technical Research Centre of Finland, P.O. Box 1000, FI-02044 VTT, Finland

Energy & Environmental Science

REVIEW

View Article Online

Towards low-cost, environmentally friendly printed chalcopyrite and kesterite solar cells

Cite this: Energy Environ. Sci., 2014, 7, 1829

Received 27th November 2013
Accepted 5th March 2014

DOI: 10.1039/c3ee43865a

www.rsc.org/ees

Hamed Azimi,*[a] Yi Hou[b] and Christoph J. Brabec[ac]

Solution-processed organic and inorganic semiconductors offer a promising path towards low-cost mass production of solar cells. Among the various material systems, solution processing of multicomponent inorganic semiconductors offers considerable promise due to their excellent electronic properties and superior photo- and thermal stability. This review surveys the recent developments of "all solution-processed" copper–indium (–gallium)-chalcogenide ($CuInS_2$, $CuInSe_2$ and Cu(In, Ga)(Se, S)$_2$) chalcopyrites and copper–zinc–tin-chalcogenide (Cu_2ZnSnS_4 and $Cu_2ZnSnSe_4$ (CZTS(e))) kesterite solar cells. A brief overview further addresses some of the most critical material aspects and associated loss mechanisms in chalcopyrite and kesterite devices. Today's state-of-the-art performance as well as future challenges to achieve low-cost and environmentally friendly production is discussed.

Broader context

[illegible]

1. Introduction

Thin film solar cell technology has a major potential for further cost reductions, provided that the expected increases in production facility size and efficiency are realized.[1–3] Fig. 1 compares the world record single cell efficiencies of various types of thin film solar cell technologies including organic, inorganic and hybrid semiconducting materials. Among the various types of thin-film solar cells, Cu(In, Ga)(Se, S)$_2$ (CIGSSe) is today the combination that delivers one of the highest power conversion efficiencies. The CIGSe world record efficiency above 20% was only recently demonstrated,[4,5] and highlighted how close CIGSe already is to poly-Si technology. Although CIGSe technology has a number of attractive features, the deposition of the absorber layer is a complex process requiring vacuum technologies. The common approach for the production of copper indium gallium diselenide (CIGSe) solar cells is currently based on the co-evaporation of individual metallic elements or on sputtering of the suitable metal precursors followed by a crystallization step at high temperature in the presence of Se vapor and/or hydrogen selenide gas (known as deposition-reaction or a sequential process). These processes are generally challenging due to the difficulty to control the film composition over a large area and the use of toxic gases for selenisation. Over the past few years, the quest for low cost production focused more and more towards the non-vacuum deposition methods. The non-vacuum approaches for deposition of multicomponent inorganic absorber layers can be generally summarized under three main categories: (I) solution deposition based on electrochemical and chemical bath-based techniques like electrodeposition, electroplating and chemical bath deposition (CBD), (II) Printing/coating from molecular-based precursor solutions, (III) Printing/coating from particulate-based solutions. Electrodeposition is one of the well-established electrochemical techniques in the electronics industry.[6] However in this method, the deposition of multicomponent semiconductors like CIGSe is generally a complex process as the different elements have different redox potentials and reduction kinetics.[7,8] Multistep deposition might be necessary to provide a good control of stoichiometry and phase homogeneity. Among the approaches mentioned, the particulate- and precursor-based approaches have recently received a great deal of attention due to their potential to simplify the fabrication processing for large-scale manufacturing.

---

[a] Institute of Materials for Electronics and Energy Technology (I-MEET), Department of Materials Science and Engineering, Friedrich-Alexander University Erlangen-Nuremberg, Martensstrasse 7, 91058 Erlangen, Germany. E-mail: hamed.azimi@fau.de

[b] Bavarian Center for Applied Energy Research (ZAE Bayern), Haberstr. 2a, 91058 Erlangen, Germany

[c] Erlangen Graduate School in Advanced Optical Technologies (SAOT), Paul-Gordan-Str. 6, 91052 Erlangen, Germany

JACS
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY
Communication
pubs.acs.org/JACS

Effective Ligand Passivation of Cu_2O Nanoparticles through Solid-State Treatment with Mercaptopropionic Acid

Hamed Azimi,*[†] Susanne Kuhri,[‡] Andres Osvet,[†] Gebhard Matt,[†] Laraib S. Khanzada,[†] Mario Lemmer,[†] Norman A. Luechinger,[§] Mats I. Larsson,[∥] Eitan Zeira,[∥] Dirk M. Guldi,[‡] and Christoph J. Brabec[†,⊥]

[†]Institute of Materials for Electronics and Energy Technology (I-MEET), Department of Materials Science and Engineering, Friedrich-Alexander University Erlangen-Nuremberg, Martensstrasse 7, 91058 Erlangen, Germany
[‡]Department of Chemistry and Pharmacy and Interdisciplinary Center for Molecular Materials, Friedrich-Alexander-University Erlangen-Nuremberg, 91058 Erlangen, Germany
[§]Nanograde Llc., Laubisrütistrasse 50, 8712 Stäfa, Switzerland
[∥]OneSun Inc., P.O. Box 1399, Sausalito, California 94966, United States
[⊥]Bavarian Center for Applied Energy Research (ZAE Bayern), Haberstr. 2a, 91058 Erlangen, Germany

Supporting Information

ABSTRACT: In colloidal nanoparticle (NP) devices, trap state densities at their surface exert a profound impact on the rate of charge carrier recombination and, consequently, on the deterioration of the device performance. Here, we report on the successful application of a ligand exchange strategy to effectively passivate the surface of cuprite (Cu_2O) NPs. Cu_2O NPs were prepared by means of a novel synthetic route based on flame spray pyrolysis. FTIR, XRD, XPS, and HRTEM measurements corroborate the formation of cubic cuprite Cu_2O nanocrystals, excluding the possible presence of undesired CuO or Cu phases. Most importantly, steady-state emission and transient absorption assays document that surface passivation results in substantial changes in the intensity of emissive excitonic states—centered at copper and oxygen vacancies—and in the lifetime of excitons near the band edge. To shed light onto ultrafast processes in Cu_2O nanocrystals additional pump probe experiments on the femtosecond and nanosecond time scales were carried out. Two discernible species were observed: on one hand, an ultrafast component (~ps) that relates to the excitons; on the other hand, a long-lived component (~μs) that originates from the defects/trap states.

Metal oxide semiconductors offer a broad range of attractive properties, including chemical stability, nontoxicity, and high abundance of elements.[1,2] Recently, special attention has been paid to preparing and probing colloidal nanoparticles (NPs) of copper oxide in the context of various photonic and photoelectrochemical applications.[3−6] Cuprous oxide (cuprite Cu_2O), which features p-type semiconducting properties and a band gap energy of about 2.1 eV, has emerged as an interesting class of materials for solar energy conversion.[7,8]

In the synthesis of cuprous oxide NPs, one of the grand challenges is the synthesis of high-quality Cu_2O NPs with minimum imperfections and the inclusion portions of impurities or undesired phases. Importantly, the formation of CuO or Cu phases on the surface of Cu_2O NPs may exceed the deleterious impact on the semiconducting properties of cuprous oxide films. In addition, important challenges in colloidal NP devices encompass the presence of an organic capping agent, on one hand, and the existence of various bulk and/or surface trap states, on the other hand. The earlier and the latter are both crucial factors that impact excited-state carrier dynamics as well as charge transport in optoelectronic devices.

Disorders, reconstructions, and uncoordinated atoms on the surface evoke the formation of shallow and deep traps in NP devices, which may adversely impact the device performance.[9] A potential solution to overcome the detrimental influence of surface traps implies the ligand passivation of NPs through a simple post-solid-state treatment. Past work has demonstrated that monovalent inorganic ligands bound to cations provide the necessary means to effectively surface passivate NPs.[10] A particularly crucial advantage of this approach is the possibility to remove dangling bonds at the NP surface without the requirements to carry out any high temperature processing steps. To date, this strategy is, however, only applied to a few inorganic NP systems such as PbS, PbSe, CdS, and CdTe NPs.[11−13] Here, we report the preparation of single phase Cu_2O nanocrystals. The dry Cu_2O nanopowder was prepared by flame spray synthesis, whereby the flame was run in nitrogen, that is, under nonoxidizing conditions, to avoid the formation of fully oxidized CuO. Cu_2O NPs were then dispersed in an acetic acid/isopropanol solvent mixture (5 wt %). The resulting mixture was centrifuged, and the supernatant was removed and replaced by dry isopropanol. The Cu_2O sediment was again dispersed with the help of horn sonication and centrifuged. After repeated washing and centrifugation, isopropanol was added in order to adjust the Cu_2O solid concentration to 5 wt %; for further details on the synthesis of Cu_2O NPs, see the Supporting Information (SI). The postsynthetic ligand exchange on thin films is exploited effectively to eliminate surface recombination sites in Cu_2O NPs.

Figure 1a shows X-ray diffraction (XRD) patterns of as-synthesized Cu_2O NPs. The observed diffraction peaks are indexed as (110), (111), (200), and (220) reflections of the

Received: March 11, 2014
Published: May 5, 2014

dx.doi.org/[illegible] | J. Am. Chem. Soc. 2014, 136, 7233−7236

JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

Article

pubs.acs.org/JACS

Qualitative Analysis of Bulk-Heterojunction Solar Cells without Device Fabrication: An Elegant and Contactless Method

Derya Baran,*[,†] Ning Li,[†] Anne-Catherine Breton,[§,‡] Andres Osvet,[†] Tayebeh Ameri,[†] Mario Leclerc,[§] and Christoph J. Brabec*[,†,‡]

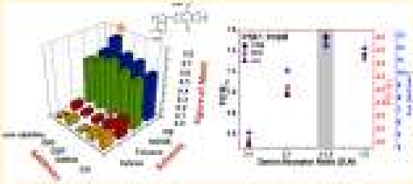
[†]Institute of Materials for Electronics and Energy Technology (i-MEET), Friedrich-Alexander-University of Erlangen-Nürnberg, Martensstrasse 7, 91058, Erlangen, GERMANY

[‡]Bavarian Center for Applied Energy Research (ZAE Bayern), Haberstr. 2a, 91058 Erlangen, GERMANY

[§]Université Laval, Department of Chemistry, Pavillon Alexandre-Vachon, Bureau 2240-C1045, Avenue de la Médecine, G1 V 0A6 Québec, QC, Canada

Supporting Information

ABSTRACT: The enormous synthetic efforts on novel solar cell materials require a reliable and fast technique for the rapid screening of novel donor/acceptor combinations in order to quickly and reliably estimate their optimized parameters. Here, we report the applicability of such a versatile and fast evaluation technique for bulk heterojunction (BHJ) organic photovoltaics (OPV) by utilizing a steady-state photoluminescence (PL) method confirmed by electroluminescence (EL) measurements. A strong relation has been observed between the residual singlet emission and the charge transfer state emission in the blend. Using this relation, a figure of merit (FOM) is defined from photoluminescence and also electroluminescence measurements for qualitative analysis and shown to precisely anticipate the optimized blend parameters of bulk heterojunction films. Photoluminescence allows contactless evaluation of the photoactive layer and can be used to predict the optimized conditions for the best polymer−fullerene combination. Most interestingly, the contactless, PL-based FOM method has the potential to be integrated as a fast and reliable inline tool for quality control and material optimization.



■ INTRODUCTION

Power conversion efficiencies (PCE) of organic photovoltaics (OPV) have already exceeded the 10% milestone.[1] This significant increase has been achieved by introducing innovative materials and device structures.[2,3] However, very few reliable techniques for the rapid screening of semiconducting materials as well as processing technologies were developed for the OPV area.[4−7] Controlling the morphology in the photoactive layer is one of the key issues to optimize the exciton harvesting, charge transfer, and charge transport processes at the donor/acceptor (D/A) interface. There are many methods, such as optimization of the D/A ratio,[8] use of different solvent mixtures,[9,10] additives,[11,12] thermal annealing,[13] among others, to control the microstructure of the photoactive layer and to improve the device performance. Yet, design and the optimization of high-performance materials is still a significant challenge for mass production of high-efficiency OPV devices. When a new polymer is introduced to the OPV field, it should be fully screened to find optimized parameters. Frequently, this is carried out with a herculean workload of complete device fabrication and characterization runs, taking a lot of time and effort. There are several techniques that can provide information on the quality of a solar cell in terms of its electrical and device properties such as charge extraction, transient photovoltage, impedance spectroscopy, and electroluminescence.[14−17] All these techniques require the completion of a full OPV device. On the other hand, there are very few rapid screening techniques which do not require electrical contacts suitable to gain insight in the PCE potential of the composites.

Photoluminescence (PL) is known as a fast, easy, and powerful spectroscopic tool which provides injection level dependent information about radiative recombination.[18] In addition, the method is contactless and is sensitive to both radiative singlet state transitions as well as low energy recombination transitions at the D/A interface. Photoluminescence from such interfacial charge transfer (CT) states (PL_{CT}) has been shown to be a sensitive probe for geminate recombination.[19−22] In addition to steady-state photoluminescence, related optical methods such as delayed photoluminescence or electroluminescence can be used to gain information related to free carrier, or nongeminate recombina-

Received: April 1, 2014
Published: July 8, 2014

dx.doi.org/10.1021/ja503134g | J. Am. Chem. Soc. 2014, 136, 10949−10955

Solar Energy Materials & Solar Cells 124 (2014) 133–137

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Quantitative imaging of shunts in organic photovoltaic modules using lock-in thermography

S. Besold*, U. Hoyer, J. Bachmann, Th. Swonke, P. Schilinsky, R. Steim, C.J. Brabec

Bavarian Center for Applied Energy Research (ZAE Bayern e.V.), Haberstraße 2a, 91058 Erlangen, Germany

ARTICLE INFO

Article history:
Received 1 July 2013
Received in revised form
7 January 2014
Accepted 18 January 2014
Available online 10 February 2014

Keywords:
Organic photovoltaics
Thermography
Simulation
Defect imaging
Parallel resistance

ABSTRACT

Thermographic methods are widely established to detect shunts in photovoltaic technologies. In all methods the cell has to be directly accessible to determine quantitative shunt values. In this manuscript a precise method is presented to determine shunt values in solar modules consisting of series connected bulk-heterojunction organic solar cells without the need to access the single cells separately. It will be shown that, although parallel resistances in organic solar cells show a strong dependence on the illumination intensity, the shunts that are detected using illuminated lock-in-thermography are strongly ohmic and therefore can be assigned a distinct ohm value.

1. Introduction

Organic photovoltaic (OPV) devices have made significant progress during the last years [1–3]. Efficiencies of more than 10% [4] prove OPV's potential to become a competitive technology to other thin film photovoltaic technologies in not far future [5,6]. The opportunity to print OPV on flexible substrates [7,8] predestines this technology for the use in building integrated photovoltaics or in consumer applications. Here the low light performance of these modules is of special importance, because the incident light situations are often less than perfect for these applications. The low light performance of OPV was shown to be very sensitive to defects affecting the parallel resistance [9]. Reduced parallel resistances or shunts reduce the voltage in the maximum power point eminently under low irradiation intensities and therefore lower disproportionally the power output and efficiency. Consequently manufacturing must pay special attention to defects leading to shunts. Thermographic methods were proven to be very well suited for spatially resolved shunt recognition of crystalline solar cells [10–12] and lately also for OPV [13,14]. In the case of photovoltaic (PV) modules, where several cells are connected in series, it is not possible to establish independent electrical access to the individual cells. Established methods to quantitatively characterize shunts are thus not applicable, without precise knowledge of the voltage in the individual cell.

In this manuscript we present a precise method to quantitatively determine shunt values in OPV modules. The method fundaments are the illumination intensity dependence of the thermographic signal for shunts.

2. Experimental

2.1. Materials and methods

Organic bulk-heterojunction modules were provided by Konarka Technologies Inc. Modules consisted of ten, in series connected cells with an active area of about 17.5 cm^2. Contact pins were inserted at interconnects to get electrical access to all the individual cells. The open circuit voltage (V_{oc}) of the modules was measured at standard test conditions (STC) using a light-emitting diode (LED) solar simulator [15]. Modules were light soaked under open circuit conditions for 15 min using a hydrargyrum quartz iodide (HQI) lamp with a light intensity of about 1000 W/m^2 before measurements. Illuminated lock-in-thermography (ILIT) measurements were done in a set-up similar to the one described in [16]. Modules were mounted on a heat sink (copper), two arrays of white LEDs were used for modulated light excitation (spectral range 400–800 nm, peak at 475 nm and high emission in the range from 485 to 670 nm). The light intensity of LED arrays was varied in the range from 1 to 81 W/m^2. The infrared (IR) radiation was detected by an IR-camera (IRCAM Equus 327kM), with an InSb-detector, sensitive in a spectral range from 1.7 to 5 µm. The IV characteristics at these different light intensities were measured in parallel by a source measurement unit (SMU) (Agilent B2901A). The image processing of the ILIT measurements was done using the software

---

* Corresponding author. Tel.: +49 9131 9398 160; fax: +49 9131 9398 199.

http://dx.doi.org/10.1016/j.solmat.2014.01.030

Solubility Based Identification of Green Solvents for Small Molecule Organic Solar Cells

*Ignasi Burgués-Ceballos, Florian Machui, Jie Min, Tayebeh Ameri, Monika M. Voigt, Yuriy N. Luponosov, Sergei A. Ponomarenko, Paul D. Lacharmoise, Mariano Campoy-Quiles, and Christoph J. Brabec**

Replacing halogenated solvents in the processing of organic solar cells by green solvents is a required step before the commercialization of this technology. With this purpose, some attempts have been made, although a general method is yet to be developed. Here, the potential of the Hansen solubility parameters (HSP) analysis for the design of green ink formulations for solution-processed active layer in bulk heterojunction photovoltaic devices based on small molecules is demonstrated. The motivation of moving towards organic small molecules stems from their lower molecular weight and more definite structure which makes them more likely to be dissolved in a wider variety of organic solvents. In the first step, the HSP of selected active materials are determined, namely, the star-shaped D-π-A tris{4-[5''-(1,1-dicyanobut-1-en-2-yl)-2,2'-bithiophen-5-yl]phenyl}amine N(Ph-2T-DCN-Et)$_3$ small molecule and fullerene derivative [6,6]-phenyl-C$_{71}$-butyric acid methyl ester (PC$_{71}$BM). Secondly, computer simulations based on HSP allow the prediction of suitable green solvents for this specific material system. The most promising green solvents, according to the simulations, are then used to fabricate solar cell devices using pristine solvents and two solvents mixtures. These devices show power conversion efficiencies around 3.6%, which are comparable to those obtained with halogenated solvents. This good performance is a result of the sufficient solubility achieved after a successful prediction of good (green) solvents.

1. Introduction

The interest in organic photovoltaic (OPV) devices based on bulk-heterojunction structures continues to increase due to its potential to become a low-cost, light-weight alternative to conventional photovoltaic technologies. Given the possibility of solution processing, an important feature of organic semiconductors is their compatibility with large-scale printing and coating processes such as roll-to-roll.[1]

Halogenated solvents such as chlorobenzene or o-dichlorobenzene have been widely used in both polymer[2] and small molecule[3] solar cells due to their well known good solubility performance. However, the toxicity of these solvents as well as their high energy consuming synthesis makes them unfavorable in terms of sustainable development. Needless to say, their ban in mass production in industrial countries with strict environmental health and safety (EHS) legislation evidences the need for green formulations. When environmentally friendly solvents can be used, there is no need for expensive housings or expensive waste disposals. In this sense, some attempts have been made in the last few years to find non-hazardous solvents to process the active layer in OPVs.[4–10] For instance, the use of pristine o-xylene and 1,2,4-trimethylbenzene for processing the workhorse P3HT:PCBM system was reported,[10] although the resulting power conversion efficiencies (2.90% with o-xylene and 1.47% with 1,2,4-trimethylbenzene) were lower than the chlorinated counterpart. Moving another step forward, the mesitylene/acetophenone solvent blend reported by Park et al.[9] showed higher efficiency for the same material system (3.38%). On the other hand, less attention has been paid by the research community on the toxicity, costs and production energy related to the synthesis of organic semiconductors. Even so, recent works on the field give interesting perspectives on costs associated to the synthesis of the active materials,[11] their life cycle embodied energy[12] and alternative green chemistry reactions.[13] The goal of this work is, however, centered around the research of green solvents for the solution processing of the active layer.

I. Burgués-Ceballos, F. Machui, J. Min, Dr. T. Ameri, Prof. C. J. Brabec
Institute Materials for Electronics and Energy Technology (i-MEET)
University Erlangen-Nürnberg
Martensstrasse 7, 91058, Erlangen, Germany
E-mail: christoph.brabec@ww.uni-erlangen.de
I. Burgués-Ceballos, Dr. P. D. Lacharmoise
Cetemmsa Technological Centre
Av. Ernest Lluch 36, 08302, Mataró, Spain
I. Burgués-Ceballos, Dr. M. Campoy-Quiles
Institut de Ciència de Materials de Barcelona
(ICMAB-CSIC), Esfera UAB, 08193, Bellaterra, Spain
Dr. M. M. Voigt, Prof. C. J. Brabec
Bavarian Center for Applied Energy Research (ZAE Bayern)
Haberstrasse 2a, 91058, Erlangen, Germany
Dr. Y. N. Luponosov, Prof. S. A. Ponomarenko
Enikolopov Institute of Synthetic Polymeric Materials
of the Russian Academy of Sciences
Profsoyuznaya 70, Moscow, 117393, Russia
Prof. S. A. Ponomarenko
Lomonosov Moscow State University
Leninskie Gory, Moscow, 119991, Russia

DOI: 10.1002/adfm.201301509

Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy 128 (2014) 197–206

Contents lists available at ScienceDirect

Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy

journal homepage: www.elsevier.com/locate/saa

Synthesis, characterization and optoelectronic properties of a new perylene diimide–benzimidazole type solar light harvesting dye

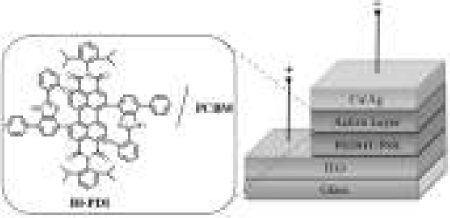
Haluk Dinçalp [a,*], Oguzhan Çimen [a], Tayebeh Ameri [b], Christoph J. Brabec [b], Sıddık İçli [c,*]

[a] Department of Chemistry, Faculty of Arts and Science, Celal Bayar University, Muradiye, 45030 Manisa, Turkey
[b] Institute of Materials for Electronics and Energy Technology (I-MEET), Friedrich-Alexander-University, Martensstraße 7, 91058 Erlangen, Germany
[c] Solar Energy Institute, Ege University, Bornova, 35100 Izmir, Turkey

HIGHLIGHTS

- Benzimidazole-substituted PDI dye for solution-processed BHJC was synthesized.
- Aggregation tendency of dye in the presence of P3HT polymer was observed.
- Electron mobility of PDI dye is calculated to be higher than the hole mobility.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 22 December 2013
Received in revised form 31 January 2014
Accepted 18 February 2014
Available online 10 March 2014

Keywords:
Perylene diimide
Benzimidazole
Photoluminescence
Charge transfer
Light harvesting
Photovoltaics

ABSTRACT

A perylene diimide type small molecule (**BI-PDI**) has been synthesized through Suzuki coupling reaction between N,N′-bis(2,6-diisopropylphenyl)-1,7-dibromoperylene-3,4,9,10-tetracarboxylic diimide and 3-(2-hydroxyphenyl)-7-phenyl-1H-benzimidazole-4-boronic acid. **BI-PDI** small molecule has showed an absorption band between 350 and 750 nm on thin films. HOMO and LUMO energy levels of **BI-PDI** dye have been calculated to be about −5.52 eV and −3.87 eV, respectively. Solution processed bulk heterojunction (BHJ) solar cells have been constructed using **BI-PDI** as donor and [6,6]-phenyl-C_{61}-butyric acid methyl ester ($PC_{61}BM$) as acceptor or poly(3-hexylthiophene) (P3HT) as donor and **BI-PDI** as acceptor. The external quantum efficiencies (EQE) of the devices cover the most of the visible region between 400 and 700 nm for both configurations. Photovoltaic performances of **BI-PDI**-based organic solar cells are limited by the aggregation tendency of PDI structure and poor hole/electron mobilities of the active layer.

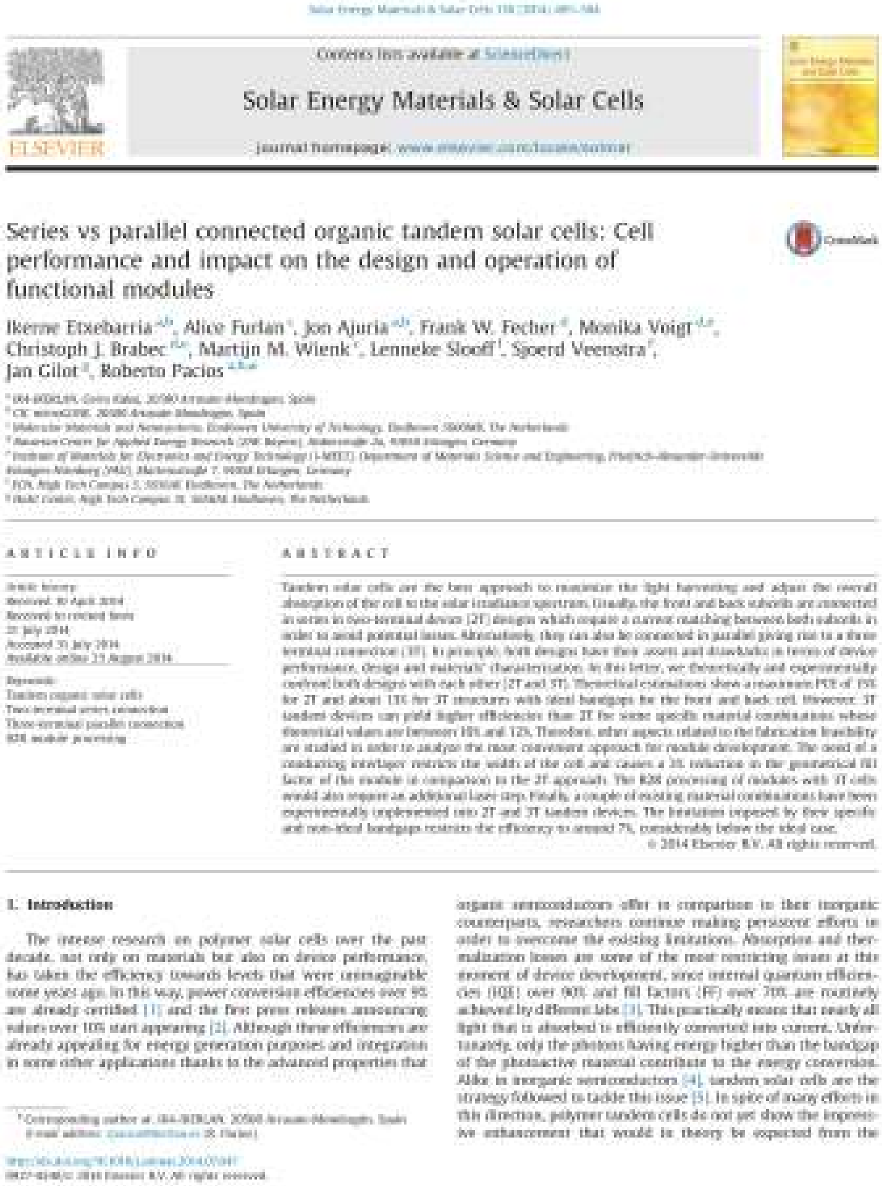
Introduction

Small molecule semiconductors have been extensively used in BHJ solar cells for decades due to their exclusively properties such as well-ordered molecular structures, simple synthetic pathways, well-defined molecular weights, easily changeable spectral tunings by variation of functional groups and advantageous on thin film morphology [1,2]. Nowadays most of the organic photovoltaic (OPV) materials have been configured by using well-known conjugated small molecules including phthalocyanines [3,4], boron-dipyrromethenes [5,6], fused acenes [7–9], thiazoles [10,11], triphenylamines [12,13], diketopyrrolopyrroles [14,15], isoindigos [16], tetraphenylphthalic-based diimides [17], and fullerenes

---

* Corresponding authors. Tel.: +90 236 2013156; fax: +90 236 2413158 (H. Dinçalp). Tel./fax: +90 232 3740 19 15 (S. İçli).
E-mail addresses: haluk.dincalp@cbu.edu.tr (H. Dinçalp), siddik.icli@ege.edu.tr (S. İçli).

http://dx.doi.org/10.1016/j.saa.2014.02.131



Solar Energy Materials & Solar Cells 130 (2014) 495–504

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Series vs parallel connected organic tandem solar cells: Cell performance and impact on the design and operation of functional modules

Ikerne Etxebarria [a,b], Alice Furlan [c], Jon Ajuria [a,b], Frank W. Fecher [d], Monika Voigt [d,e], Christoph J. Brabec [d,e], Martijn M. Wienk [c], Lenneke Slooff [f], Sjoerd Veenstra [f], Jan Gilot [g], Roberto Pacios [a,b,*]

[a] IK4-IKERLAN, Goiru Kalea, 20500 Arrasate-Mondragon, Spain
[b] CIC microGUNE, 20500 Arrasate-Mondragon, Spain
[c] Molecular Materials and Nanosystems, Eindhoven University of Technology, Eindhoven 5600MB, The Netherlands
[d] Bavarian Center for Applied Energy Research (ZAE Bayern), Haberstraße 2a, 91058 Erlangen, Germany
[e] Institute of Materials for Electronics and Energy Technology (i-MEET), Department of Materials Science and Engineering, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Martensstraße 7, 91058 Erlangen, Germany
[f] ECN, High Tech Campus 5, 5656AE Eindhoven, The Netherlands
[g] Holst Centre, High Tech Campus 31, 5656AE Eindhoven, The Netherlands

ARTICLE INFO

Article history:
Received 10 April 2014
Received in revised form
21 July 2014
Accepted 31 July 2014
Available online 23 August 2014

Keywords:
Tandem organic solar cells
Two-terminal series connection
Three-terminal parallel connection
R2R module processing

ABSTRACT

Tandem solar cells are the best approach to maximize the light harvesting and adjust the overall absorption of the cell to the solar irradiance spectrum. Usually, the front and back subcells are connected in series in two-terminal device (2T) designs which require a current matching between both subcells in order to avoid potential losses. Alternatively, they can also be connected in parallel giving rise to a three-terminal connection (3T). In principle, both designs have their assets and drawbacks in terms of device performance, design and materials' characterization. In this letter, we theoretically and experimentally confront both designs with each other (2T and 3T). Theoretical estimations show a maximum PCE of 15% for 2T and about 13% for 3T structures with ideal bandgaps for the front and back cell. However, 3T tandem devices can yield higher efficiencies than 2T for some specific material combinations whose theoretical values are between 10% and 12%. Therefore, other aspects related to the fabrication feasibility are studied in order to analyze the most convenient approach for module development. The need of a conducting interlayer restricts the width of the cell and causes a 3% reduction in the geometrical fill factor of the module in comparison to the 2T approach. The R2R processing of modules with 3T cells would also require an additional laser step. Finally, a couple of existing material combinations have been experimentally implemented into 2T and 3T tandem devices. The limitation imposed by their specific and non-ideal bandgaps restricts the efficiency to around 7%, considerably below the ideal case.

1. Introduction

The intense research on polymer solar cells over the past decade, not only on materials but also on device performance, has taken the efficiency towards levels that were unimaginable some years ago. In this way, power conversion efficiencies over 9% are already certified [1] and the first press releases announcing values over 10% start appearing [2]. Although these efficiencies are already appealing for energy generation purposes and integration in some other applications thanks to the advanced properties that organic semiconductors offer in comparison to their inorganic counterparts, researchers continue making persistent efforts in order to overcome the existing limitations. Absorption and thermalization losses are some of the most restricting issues at this moment of device development, since internal quantum efficiencies (IQE) over 90% and fill factors (FF) over 70% are routinely achieved by different labs [3]. This practically means that nearly all light that is absorbed is efficiently converted into current. Unfortunately, only the photons having energy higher than the bandgap of the photoactive material contribute to the energy conversion. Alike in inorganic semiconductors [4], tandem solar cells are the strategy followed to tackle this issue [5]. In spite of many efforts in this direction, polymer tandem cells do not yet show the impressive enhancement that would in theory be expected from the

---

[*] Corresponding author at: IK4-IKERLAN, 20500 Arrasate-Mondragón, Spain.
E-mail address: rpacios@ikerlan.es (R. Pacios).

http://dx.doi.org/10.1016/j.solmat.2014.07.047

Available online at www.sciencedirect.com
ScienceDirect
Solar Energy 105 (2014) 494–504
SOLAR ENERGY
www.elsevier.com/locate/solener

Influence of a shunt on the electrical behavior in thin film photovoltaic modules – A 2D finite element simulation study

Frank W. Fecher[a,b,*], Alexander Pérez Romero[a], Christoph J. Brabec[a,b], Claudia Buerhop-Lutz[a]

[a] *Bayerisches Zentrum für Angewandte Energieforschung e.V. (ZAE Bayern), Haberstraße 2a, 91058 Erlangen, Germany*
[b] *Lehrstuhl für Werkstoffe der Elektronik und Energietechnik (i-MEET), Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Martensstraße 7, 91058 Erlangen, Germany*

Received 7 January 2014; received in revised form 7 April 2014; accepted 13 April 2014
Available online 8 May 2014

Communicated by: Associate Editor Igor Tyukhov

Abstract

Despite significant efficiency improvements of thin film photovoltaic modules over the last years, this technology struggles with the same problem – shunts that lower the output power dramatically. In this work, we studied the influence of a single shunt on the module performance by electrical 2D finite element simulations. By varying parameters such as irradiance, shunt resistance, shunt position and shunt size a profound understanding of the shunt's impact on the module performance was achieved. Most remarkable is the dependence of the module's output performance on the local shunt position, which can make up to 25% of the losses. Such high losses are caused by "circular" lateral currents in the electrode layers that spread in the shunted as well as into the neighboring cells. We show that the shunt's position inside the cell determines the geometry of the lateral currents and, consequently, the shunt's influence region.

The finite element model presented here was developed on the basis of CIGS thin film modules, but the results are qualitatively valid for other monolithically series connected thin film module technologies like CdTe or a-Si:H.

Keywords: 2D finite element simulation; Thin film photovoltaic module; Shunt defect; Electrical performance

1. Introduction

The success of thin film modules is based on their low production cost and relative high efficiency. These facts are based on low demand of material and the monolithic module production (Razykov et al., 2011; Scheer, 2012). Nevertheless, the modules are affected by defects occurring in the production processes or later during operation in the field. One prominent representative of those device defects is an ohmic shunt, which acts as a short circuit in the solar cell, lowering the output performance of the cell dramatically. For this reason, it is worth looking at those shunts in more detail and investigating their influence on the performance of monolithic thin film modules.

Previously, experimental investigations on CuInGaSe$_2$ (CIGS)-modules were reported using infrared (IR)-thermography and electroluminescence (EL) to characterize the shunts (Buerhop et al., 2012; Helbig et al., 2010; Tran et al., 2011). In this paper, we provide comprehensive simulation results to describe the shunt's impact on the module performance. The simulations feature a systematic

---

[*] Corresponding author at: Bayerisches Zentrum für Angewandte Energieforschung e.V. (ZAE Bayern), Haberstraße 2a, 91058 Erlangen, Germany. Tel.: +49 9131 9398 178.
E-mail address: frank.fecher@zae-bayern.de (F.W. Fecher).

http://dx.doi.org/10.1016/j.solener.2014.04.011

ACS APPLIED MATERIALS & INTERFACES

Research Article

www.acsami.org

Fully Solution-Processing Route toward Highly Transparent Polymer Solar Cells

Fei Guo,*[†] Peter Kubis,[†,‡] Tobias Stubhan,[†] Ning Li,[†] Derya Baran,[†] Thomas Przybilla,[§] Erdmann Spiecker,[§] Karen Forberich,[†] and Christoph J. Brabec*[,†,#]

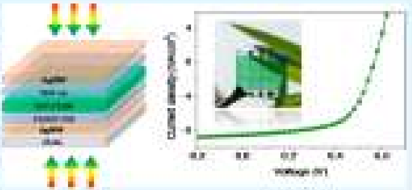
[†]Institute of Materials for Electronics and Energy Technology (i-MEET), Friedrich-Alexander-University Erlangen-Nuremberg, Martensstrasse 7, 91058 Erlangen, Germany

[‡]Erlangen Graduate School in Advanced Optical Technologies (SAOT), Friedrich-Alexander-University Erlangen-Nuremberg, Paul-Gordan-Strasse 6, 91052 Erlangen, Germany

[§]Center for Nanoanalysis and Electron Microscopy (CENEM), University Erlangen-Nuremberg, Cauerstraße 6, 91058 Erlangen, Germany

[#]Bavarian Center for Applied Energy Research (ZAE Bayern), Haberstrasse 2a, 91058 Erlangen, Germany

Supporting Information



ABSTRACT: We report highly transparent polymer solar cells using metallic silver nanowires (AgNWs) as both the electron- and hole-collecting electrodes. The entire stack of the devices is processed from solution using a doctor blading technique. A thin layer of zinc oxide nanoparticles is introduced between photoactive layer and top AgNW electrode which plays decisive roles in device functionality: it serves as a mechanical foundation which allows the solution-deposition of top AgNWs, and more importantly it facilitates charge carriers extraction due to the better energy level alignment and the formation of ohmic contacts between the active layer/ZnO and ZnO/AgNWs. The resulting semitransparent polymer:fullerene solar cells showed a power conversion efficiency of 2.9%, which is 72% of the efficiency of an opaque reference device. Moreover, an average transmittance of 41% in the wavelength range of 400−800 nm is achieved, which is of particular interest for applications in transparent architectures.

KEYWORDS: *semitransparent polymer solar cells, fully solution-processing, OPV, ITO-free*

1. INTRODUCTION

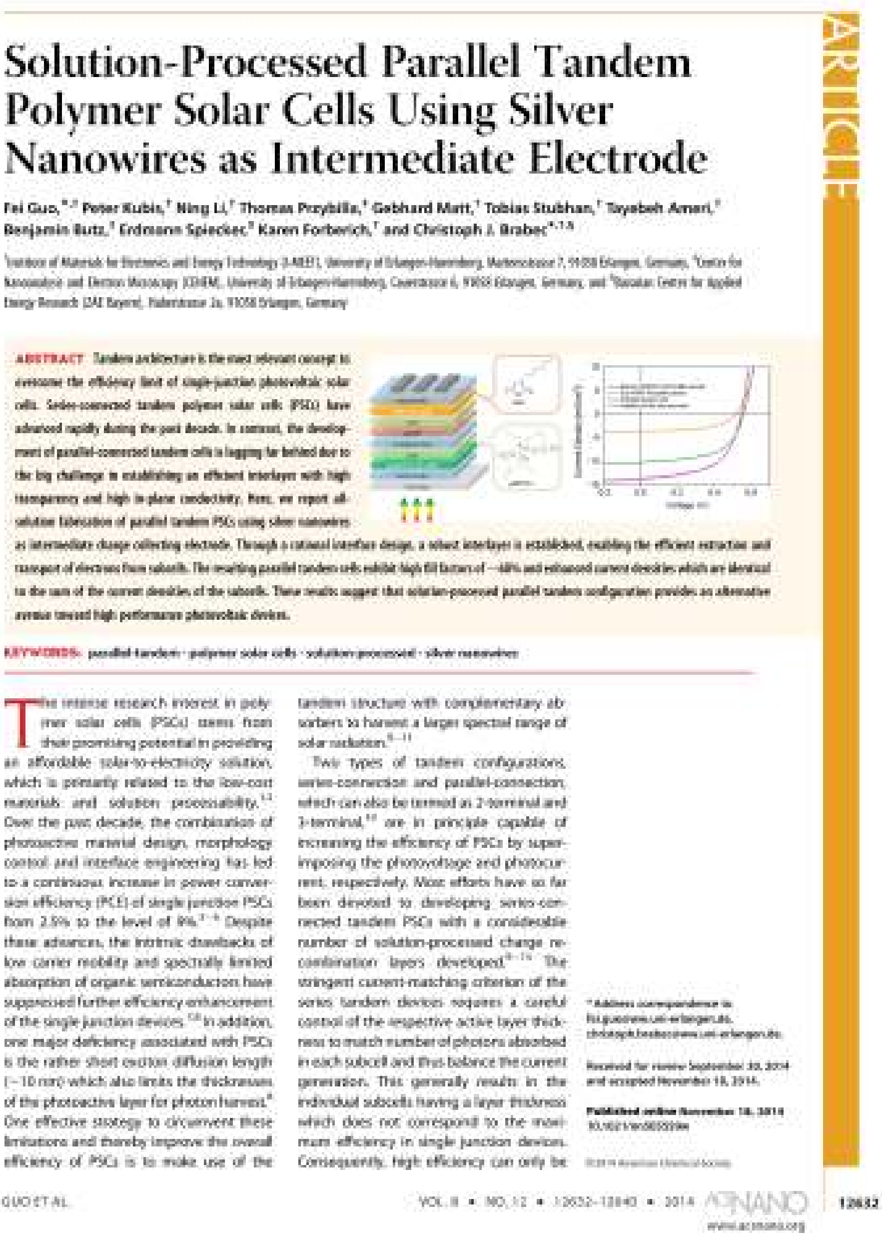
Bulk-heterojunction polymer solar cells (PSCs) have been recognized as an attractive solar technology because of the promise of low-cost materials and easy processing requirements.[1,2] The intrinsic features of color tunability and semitransparency of the thin photoactive films turn out to be a great asset for PSCs. These characteristics enable the manufacturing of differently colored semitransparent PSCs (ST-PSCs) by applying two transparent electrodes.[3−10] In addition to traditional applications similar to inorganic panels, aesthetic ST-PSCs are quite appealing power generators for various transparent architectures, such as windows, glass roof tops, curtain walls, shades, self-powered greenhouses, etc. Because of these specific applications, ST-PSCs have recently attracted growing attention and are considered as a high priority for organic photovoltaics (OPV).

By employing high-performance photoactive polymers,[4−6] tandem structures,[7−9] and advanced light management,[10−12] the power conversion efficiency (PCE) of ST-PSCs was steadily increased to over 7%. Despite this progress in pursuing high efficiencies, only a few reports have focused on the low-cost solution-processing of the entire device stack. Many reported ST-PSCs currently employ commercial indium tin oxide (ITO) as bottom electrodes combined with a vacuum deposited or sputtered transparent top electrodes, i.e., ITO or thin metal films.[3−10] However, the utilization of expensive ITO (caused by the scarce indium and the involved sputter and tempering procedures) and energy-consuming deposition of top electrodes are unfavorable to fulfill the cost potential of the PSC technology. Accordingly, it is highly desired that a cost-effective fully solution-processing route that is compatible with roll-to-roll manufacturing can be developed to fabricate semitransparent solar cells.

To realize fully solution-processed ST-PSCs, the selection of electrode materials and corresponding processing technique are the two important considerations. Several solution-processable electrodes,[13−20] such as carbon nanotubes, graphene, printed silver grids, highly conductive poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS), metallic nanowires/nanoparticles, etc., have been

Received: August 11, 2014
Accepted: September 18, 2014
Published: September 18, 2014

dx.doi.org/10.1021/[illegible] | ACS Appl. Mater. Interfaces 2014, 6, 18251−18257



Solution-Processed Parallel Tandem Polymer Solar Cells Using Silver Nanowires as Intermediate Electrode

Fei Guo,*,† Peter Kubis,† Ning Li,† Thomas Przybilla,‡ Gebhard Matt,† Tobias Stubhan,† Tayebeh Ameri,† Benjamin Butz,‡ Erdmann Spiecker,‡ Karen Forberich,† and Christoph J. Brabec*,†,§

†Institute of Materials for Electronics and Energy Technology (i-MEET), University of Erlangen-Nuremberg, Martensstrasse 7, 91058 Erlangen, Germany, ‡Center for Nanoanalysis and Electron Microscopy (CENEM), University of Erlangen-Nuremberg, Cauerstrasse 6, 91058 Erlangen, Germany, and §Bavarian Center for Applied Energy Research (ZAE Bayern), Haberstrasse 2a, 91058 Erlangen, Germany

ABSTRACT Tandem architecture is the most relevant concept to overcome the efficiency limit of single-junction photovoltaic solar cells. Series-connected tandem polymer solar cells (PSCs) have advanced rapidly during the past decade. In contrast, the development of parallel-connected tandem cells is lagging far behind due to the big challenge in establishing an efficient interlayer with high transparency and high in-plane conductivity. Here, we report all-solution fabrication of parallel tandem PSCs using silver nanowires as intermediate charge collecting electrode. Through a rational interface design, a robust interlayer is established, enabling the efficient extraction and transport of electrons from subcells. The resulting parallel tandem cells exhibit high fill factors of ~60% and enhanced current densities which are identical to the sum of the current densities of the subcells. These results suggest that solution-processed parallel tandem configuration provides an alternative avenue toward high performance photovoltaic devices.

KEYWORDS: parallel tandem · polymer solar cells · solution processed · silver nanowires

The intense research interest in polymer solar cells (PSCs) stems from their promising potential in providing an affordable solar-to-electricity solution, which is primarily related to the low-cost materials and solution processability.[1,2] Over the past decade, the combination of photoactive material design, morphology control and interface engineering has led to a continuous increase in power conversion efficiency (PCE) of single junction PSCs from 2.5% to the level of 9%.[3−6] Despite these advances, the intrinsic drawbacks of low carrier mobility and spectrally limited absorption of organic semiconductors have suppressed further efficiency enhancement of the single junction devices.[7,8] In addition, one major deficiency associated with PSCs is the rather short exciton diffusion length (~10 nm) which also limits the thickness of the photoactive layer for photon harvest.[8] One effective strategy to circumvent these limitations and thereby improve the overall efficiency of PSCs is to make use of the tandem structure with complementary absorbers to harvest a larger spectral range of solar radiation.[9−11]

Two types of tandem configurations, series-connection and parallel-connection, which can also be termed as 2-terminal and 3-terminal,[12] are in principle capable of increasing the efficiency of PSCs by superimposing the photovoltage and photocurrent, respectively. Most efforts have so far been devoted to developing series-connected tandem PSCs with a considerable number of solution-processed charge recombination layers developed.[9−16] The stringent current-matching criterion of the series tandem devices requires a careful control of the respective active layer thickness to match number of photons absorbed in each subcell and thus balance the current generation. This generally results in the individual subcells having a layer thickness which does not correspond to the maximum efficiency in single junction devices. Consequently, high efficiency can only be

Received for review September 30, 2014 and accepted November 18, 2014.

GUO ET AL. VOL. 8 • NO. 12 • 12632–12640 • 2014 ACSNANO www.acsnano.org 12632

Energy & Environmental Science

COMMUNICATION

View Article Online
View Journal | View Issue

Cite this: Energy Environ. Sci., 2014, 7, 2974

Received 18th June 2014
Accepted 9th July 2014

DOI: 10.1039/c4ee01842g

www.rsc.org/ees

Reducing burn-in voltage loss in polymer solar cells by increasing the polymer crystallinity†

Thomas Heumueller,[ab] William R. Mateker,[a] I. T. Sachs-Quintana,[a] Koen Vandewal,[a] Jonathan A. Bartelt,[a] Timothy M. Burke,[a] Tayebeh Ameri,[b] Christoph J. Brabec[bc] and Michael D. McGehee*[a]

In order to commercialize polymer solar cells, the fast initial performance losses present in many high efficiency materials will have to be managed. This burn-in degradation is caused by light-induced traps and its characteristics depend on which polymer is used. We show that the light-induced traps are in the bulk of the active layer and we find a direct correlation between their presence and the open-circuit voltage loss in devices made with amorphous polymers. Solar cells made with crystalline polymers do not show characteristic open circuit voltage losses, even though light-induced traps are also present in these devices. This indicates that crystalline materials are more resistant against the influence of traps on device performance. Recent work on crystalline materials has shown there is an energetic driving force for charge carriers to leave amorphous, mixed regions of bulk heterojunctions, and charges are dominantly transported in pure, ordered phases. This energetic landscape allows efficient charge generation as well as extraction and also may benefit the stability against light-induced traps.

Broader context

Organic photovoltaics (OPV) are a promising technology with the potential for large scale production at very low cost. An industrial application of this technology could significantly contribute to the global energy production but was impeded by low efficiencies and lifetimes of organic photovoltaics. With power conversion efficiencies recently surpassing 10%, it is now imperative to investigate and improve the lifetime of polymer–fullerene solar cells. The lifetime of OPV can depend on many variables and results between different laboratories are sometimes difficult to compare. We show how to distinguish multiple simultaneously occurring degradation mechanisms and how to identify their influence on different device parameters. We find that a high degree of crystallinity significantly reduces the initial light induced burn-in degradation which provides a general design rule for organic solar cells.

1. Introduction

Organic bulk heterojunction solar cells recently surpassed efficiencies of 10%.[1,2] The stability of organic solar cells is also of significant importance.[3–5] Recent investigations on several high performing materials for organic solar cells showed severe efficiency losses of up to 25% during the initial phase of operation.[6–8] For electronic devices with fast initial failure, a burn-in[9] step is often performed by the manufacturer to provide a more reliable product to the customer. Referring to this practice, the initial degradation in OPV devices has been termed a "burn-in"[7] period. This burn-in degradation is a severe limitation for the efficiency of organic photovoltaic modules. Understanding and limiting the burn-in losses will be a crucial step toward commercialization of organic photovoltaics.

Several different degradation mechanisms of organic solar cells can be distinguished. Besides extrinsic factors like reactions with oxygen,[10–13] intrinsic reactions are of high importance, as they limit the stability of encapsulated devices. Interface degradation is well studied for metal electrodes and PEDOT:PSS,[4] but more research has to be done on solution processable metal oxide contact materials.[14] Another important mechanism is thermal degradation, which occurs above the glass transition temperature (T_g) of a polymer and induces morphological changes like phase separation.[15] For polymers with low T_g, like P3HT, thermal degradation can be observed at typical solar cell operating conditions.[7] In light ageing experiments below the T_g of PCDTBT no morphological changes were observed in X-ray diffraction experiments.[8] Finally, light-induced degradation is highly important, since solar cells operate under relatively high photon fluxes. Recent research has proposed both general mechanisms for light-induced degradation in all polymers[16,17] and more specific reactions[18–21] in various materials, including crosslinking[22] and fullerene dimerization.[23] A conclusive explanation of the mechanisms behind light-induced degradation, however, is still missing.

---

[a] Department of Materials Science and Engineering, Stanford University, Stanford, CA 94305, USA. E-mail: mmcgehee@stanford.edu

[b] i-MEET, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen, Germany

[c] Bayerisches Zentrum für Angewandte Energieforschung, Erlangen, Germany

† Electronic supplementary information (ESI) available. See DOI: 10.1039/c4ee01842g

Organic Electronics 15 (2014) 2256–2263

Contents lists available at ScienceDirect

Organic Electronics

journal homepage: www.elsevier.com/locate/orgel

High precision processing of flexible P3HT/PCBM modules with geometric fill factor over 95%

Peter Kubis[a,d,*], Luca Lucera[b], Florian Machui[a], George Spyropoulos[a], Johann Cordero[a], Alfred Frey[c], Joachim Kaschta[c], Monika M. Voigt[a,1], Gebhard J. Matt[a], Eitan Zeira[e], Christoph J. Brabec[a,b]

[a] Institute of Materials for Electronics and Energy Technology (i-MEET), Friedrich-Alexander-University Erlangen-Nuremberg, Martensstrasse 7, 91058 Erlangen, Germany
[b] Bavarian Center for Applied Energy Research (ZAE Bayern), Haberstr. 2a, 91058 Erlangen, Germany
[c] Institute of Polymer Materials (LSP), Friedrich-Alexander-University Erlangen-Nuremberg, Martensstrasse 7, 91058 Erlangen, Germany
[d] Erlangen Graduate School in Advanced Optical Technologies (SAOT), Paul-Gordan-Str. 6, 91052 Erlangen, Germany
[e] OneSun Solar Inc., P.O. Box 1330, Sunnyvale, CA 94086, USA

ARTICLE INFO

Article history:
Received 4 May 2014
Received in revised form 4 June 2014
Accepted 7 June 2014
Available online 26 June 2014

Keywords:
Flexible transparent electrode
Flexible OPV module
Slot die coating
Ultra-fast Laser patterning
High geometric fill factor

ABSTRACT

Flexible OPV modules, based on P3HT:PCBM as absorber layer, were manufactured with a power conversion efficiency over 3% and for a total area of 3500 mm^2 consisting of 14 in series interconnected cells. The modules utilize the excellent mechanical and the outstanding optical properties of sputtered transparent ITO-Metal-ITO (IMI) electrodes deposited on the PET foil on the one hand, and the combination of large area slot-die coating with high resolution ultrafast laser patterning on the other hand. The manufacturing of modules with outstanding performance was found to be reproducible. The right combination of innovative electrodes and smart roll-to-roll compatible processing technologies demonstrates a viable path towards high efficient industrial module technology.

1. Introduction

In the last years we have witnessed an incredible development in the efficiency of organic photovoltaic (OPV) devices exceeding 10% [1–3] but these records were achieved on small lab scale devices and are significant only in terms of research and development. However, large scale modules with comparable efficiency to small scale devices are relevant for industrial and commercial applications. Therefore it is necessary to develop a production technology which can efficiently utilize the current state of the art of device manufacturing and transfer it to the module level.

In recent years many efforts had been made to investigate solution processed OPV devices using sheet-to-sheet (S2S) or roll-to-roll (R2R) coating [5,6,4,7,22–24] but the demonstrated devices were typically 20–30% less efficient than the corresponding single cells fabricated with the traditional laboratory technique, the doctor blade. The main reason for the efficiency drop, independent of the good quality of coating, was related to the high sheet resistivity of the transparent electrode and the low resolution of patterning [5,4,22,23].

Today indium tin oxide (ITO) coated polyethylene terephthalate (PET) foil [6] and solution processed high conductive poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS) in combination with a printed

---

* Corresponding author at: Institute of Materials for Electronics and Energy Technology (i-MEET), Friedrich-Alexander-University Erlangen-Nuremberg, Martensstrasse 7, 91058 Erlangen, Germany. Tel.: +49 91318527634; fax: +49 91318528495.

E-mail address: peter.kubis@fau.de (P. Kubis).

http://dx.doi.org/10.1016/j.orgel.2014.06.008

Environmentally Printing Efficient Organic Tandem Solar Cells with High Fill Factors: A Guideline Towards 20% Power Conversion Efficiency

Ning Li, Derya Baran, George D. Spyropoulos, Hong Zhang, Stephane Berny, Mathieu Turbiez, Tayebeh Ameri, Frederik C. Krebs, and Christoph J. Brabec*

The tandem concept involves stacking two or more cells with complementary absorption spectra in series or parallel connection, harvesting photons at the highest possible potential. It is strongly suggested that the roll-to-roll production of organic solar cells will employ the tandem concept to enhance the power conversion efficiency (PCE). However, due to the undeveloped deposition techniques, the challenges in ink formulation as well as the lack of commercially available high performance active materials, roll-to-roll fabrication of highly efficient organic tandem solar cells currently presents a major challenge. The reported high PCE values from lab-scale spin-coated devices are, of course, representative, but not helpful for commercialization. Here, organic tandem solar cells with exceptionally high fill factors and PCE values of 7.66% (on glass) and 5.56% (on flexible substrate), which are the highest values for the solution-processed tandem solar cells fabricated by a mass-production compatible coating technique under ambient conditions, are demonstrated. To predict the highest possible performance of tandem solar cells, optical simulation based on experimentally feasible values is performed. A maximum PCE of 21% is theoretically achievable for an organic tandem solar cell based on the optimized bandgaps and achieved fill factors.

1. Introduction

Organic photovoltaics (OPV) attracted increasing research interest in the last decade owing to its unique advantages over its inorganic counterpart, such as low cost, lightweight and easy manufacturing on a large-scale.[1–4] The power conversion efficiencies (PCEs) of OPV devices already surpassed the 10% milestone,[5] occupying an important position in energy infrastructure in the near future. However, the commonly used deposition method, i.e., spin-coating in inert atmosphere, is not compatible with mass-production technology such as roll-to-roll production.[6,7] Thus, the research on large-scale produced OPV devices at the moment lags far behind the state-of-the-art devices. It is obvious that significant efforts have to be made when progressing from lab-scale to roll-to-roll production.[7,8]

The tandem concept, in which single-junction solar cells with complementary absorption spectra are stacked together either in series or in parallel, was recently proven to simultaneously tackle the two main loss mechanisms in organic solar cells, i.e., losses due to narrow absorption of donor materials as well as thermalization losses.[9] According to previous predictions, tandem solar cells are supposed to achieve a theoretical PCE of 15%,[10] while the PCE of single-junction solar cells is calculated to be of 10–11% under the same conditions.[11] Recently, several research groups have reported solution-processed organic tandem solar cells with PCEs in the range of 8–10%,[12–15] higher than the performance of corresponding single-junction cells. This is a strong argument for large-scale production of organic solar cells using the

N. Li, D. Baran, H. Zhang, Dr. T. Ameri, Prof. C. J. Brabec
Institute of Materials for Electronics and
Energy Technology (i-MEET)
Friedrich-Alexander-University Erlangen-Nuremberg
Martensstraße 7, 91058 Erlangen, Germany
E-mail: ning.li@fau.de
G. D. Spyropoulos, Prof. C. J. Brabec
Bavarian Center for Applied Energy Research (ZAE Bayern)
Haberstraße 2a, 91058 Erlangen, Germany
H. Zhang
Erlangen Graduate School in Advanced Optical Technologies (SAOT)
Paul-Gordan-Straße 6
91052, Erlangen, Germany

Dr. S. Berny
Merck Chemicals Ltd., Chilworth Technical Centre
University Parkway
Southampton SO16 7QD, UK
Dr. M. Turbiez
BASF Schweiz AG
Schwarzwaldallee 215, CH-4002, Basel, Switzerland
Prof. F. C. Krebs
Department of Energy Conversion and Storage
Technical University of Denmark
Frederiksborgvej 399, DK-4000 Roskilde, Denmark

DOI: 10.1002/aenm.201400084

Solar Energy Materials & Solar Cells 120 (2014) 701–708

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Towards large-scale production of solution-processed organic tandem modules based on ternary composites: Design of the intermediate layer, device optimization and laser based module processing

Ning Li[a,*], Peter Kubis[a,d,1], Karen Forberich[a], Tayebeh Ameri[a], Frederik C. Krebs[b], Christoph J. Brabec[a,c]

[a] Institute of Materials for Electronics and Energy Technology (i-MEET), Friedrich-Alexander-University Erlangen-Nuremberg, Martensstraße 7, 91058 Erlangen, Germany
[b] Department of Energy Conversion and Storage, Technical University of Denmark, Frederiksborgvej 399, DK-4000 Roskilde, Denmark
[c] Bavarian Center for Applied Energy Research (ZAE Bayern), Haberstraße 2a, 91058 Erlangen, Germany
[d] Erlangen Graduate School in Advanced Optical Technologies (SAOT), Paul-Gordan-Straße 6, 91052 Erlangen, Germany

ARTICLE INFO

Available online 2 October 2013

Keywords:
Solution processing
Organic tandem solar cells
Intermediate layer
Ternary composites
Optical simulation
Laser-based module processing

ABSTRACT

We report on a novel approach including: 1. the design of an efficient intermediate layer, which facilitates the use of most high performance active materials in tandem structure and the compatibility of the tandem concept with large-scale production; 2. the concept of ternary composites based on commercially available materials, which enhances the absorption of poly(3-hexylthiophene) (P3HT) and as a result increase the PCE of the P3HT-based large-scale OPV devices; 3. laser-based module processing, which provides an excellent processing resolution and as a result can bring the power conversion efficiency (PCE) of mass-produced organic photovoltaic (OPV) devices close to the highest PCE values achieved for lab-scale solar cells through a significant increase in the geometrical fill factor. We believe that the combination of the above mentioned concepts provides a clear roadmap to push OPV towards large-scale production and commercial applications.

1. Introduction

In the last decade organic photovoltaic (OPV) has attracted more and more attention in the research community owing to its remarkable advantages compared to conventional photovoltaics, such as low cost, light weight and easy large-scale production [1–4]. The power conversion efficiency (PCE) of lab-scale OPV devices has reached ~8–10% [5–8] by the development of novel donor materials and meticulous device optimization, indicating a bright future for OPV devices in commercial applications.

As the most studied active material, poly(3-hexylthiophene):phenyl-C_{61}-butyric acid methyl ester (P3HT:[60]PCBM) is one of the most promising candidates until now for large-scale production because of the commercial availability, low cost and easy processing in air. However, the P3HT:[60]PCBM-based OPV devices give an averaged PCE of ~3% for the lab-scale solar cells [9] and of ~2% for the mass-produced OPV devices [10]. The PCE of P3HT:PCBM-based OPV devices is limited by the narrow absorption of P3HT, which results in a decreased short circuit current (J_{sc}), and thermalization losses, which result in a decreased open circuit voltage (V_{oc}). Obviously, compared to the > 10% PCE reported for the lab-scale solar cells [8] the PCE of mass-produced OPV devices is still at an initial stage, which is mainly due to the lack of commercially available high performance active materials and non-optimized processing techniques with a low degree of control.

The tandem concept, which involves stacking two or more cells with complementary absorption spectra in serial or parallel connection [11,12], has been proven to simultaneously address both loss-mechanisms of OPV devices: the narrow absorption window and the thermalization losses. Recently, the PCE of lab-scale OPV devices has surpassed the 12% milestone by using the tandem concept (press release by Heliatek), which has the potential to boost the PCE of OPV devices towards the expected efficiency of 15% [13], while the PCE of mass-production compatible single-junction devices is restricted to 10–11% [14]. The intermediate layer (IML) consisting of a hole- and an electron-transporting layer is considered to lie at the heart of the tandem structure. The holes and electrons that are selectively collected by the IML should recombine efficiently at its interface [12]. Increasing the PCE of tandem devices toward 15% theoretical efficiency requires the design of efficient and reliable IMLs. We

---

* Corresponding author. Tel.: +49 9131 85 27634; fax: +49 9131 85 28495.
E-mail address: Ning.Li@ww.uni-erlangen.de (N. Li).

0927-0248/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.solmat.2013.09.019

Journal of
Materials Chemistry A

ROYAL SOCIETY
OF CHEMISTRY

PAPER

View Article Online
View Journal | View Issue

Cite this: J. Mater. Chem. A, 2014, 2, 14896

A universal method to form the equivalent ohmic contact for efficient solution-processed organic tandem solar cells†

Ning Li,*[a] Tobias Stubhan,[a] Johannes Krantz,[a] Florian Machui,[a] Mathieu Turbiez,[b] Tayebeh Ameri[a] and Christoph J. Brabec[ac]

Received 23rd June 2014
Accepted 11th July 2014

DOI: 10.1039/c4ta03182b

www.rsc.org/MaterialsA

The highly transparent, conductive and robust intermediate layer (IML) is the primary challenge for constructing efficient organic tandem solar cells. In this work, we demonstrate an easy but generic approach to realize the fully functional, solution-processed IMLs. In detail, solution-processed silver-nanowires are packed at low concentration between hole- and electron-transporting layers to convert an otherwise rectifying interface into an ohmic interface. The IMLs are proven to be of ohmic nature under applied bias, despite the unipolar charge selectivity of the single layers. Ohmic recombination within IMLs is further proven in organic tandem solar cells fabricated by doctor-blading under ambient conditions. The tandem solar cells based on PCDTBT:[70]PCBM as the bottom cell and pDPP5T-2:[60]PCBM as the top cell give a power conversion efficiency of 7.25%, which is among the highest values for solution-processed organic tandem solar cells fabricated by using a roll-to-roll compatible deposition method in air.

Introduction

The rapid growth in the field of organic photovoltaics (OPV) has attracted more and more attention from worldwide researchers during the last decade due to their large-scale, low-cost and easy manufacturing properties.[1–4] It has been reported that the power conversion efficiency (PCE) of OPV devices has already surpassed the 10% milestone, which shows enormous promise and potential for commercial applications.[5,6] The PCE limitations of OPV devices are mainly due to the narrow absorption spectra of the donor materials, resulting in decreased short circuit current density (J_{sc}) and the thermalization losses, resulting in decreased open circuit voltage (V_{oc}).[7,8] The reduced J_{sc} can be addressed by ternary or multicomponent donor–acceptor systems, which were successfully shown to broaden the absorption of organic semiconductor composites.[9–11] The thermalization losses are more complex to tackle. Hummelen et al. recently suggested the design of organic semiconductors with high dielectric constant to reduce losses related to the exciton binding energy.[12] Another approach is the tandem concept, which stacks two or more cells with complementary absorption spectra in series or parallel connection. This concept addresses both losses: the J_{sc} related absorption losses as well as the V_{oc} related thermalization losses. In the last few years, a number of organic tandem solar cells with high efficiencies were reported,[5,13–21] and the efficiency roadmap for tandem cells is clearly pointing towards the predicted 15%.[22]

To realize high performance organic tandem solar cells, an efficient and reliable intermediate layer (IML) is required, which is typically designed from a series-connected sequence of a hole-transporting layer (HTL) and an electron-transporting layer (ETL).[23] The performance of an organic tandem solar cell is strongly dependent on the quality and functionality of its IML. Ideally, the IML should be highly transparent, conductive and robust enough to protect the underlying semiconductor layer and to form a quasi ohmic contact between HTL and ETL.[24] The majority of novel active layer materials are sensitive to humidity and oxygen at elevated temperatures and the microstructure of the semiconductor layer might be negatively influenced by the high temperature processing.[25] Therefore the fabrication of efficient organic tandem solar cells including the IML should avoid high temperature steps.

Although many efforts have been made to understand the recombination properties of IMLs, utilizing commonly used buffer layers to form the quasi ohmic contact in a general way is still a problem for solution-processed tandem solar cells. Today's reference materials for the IMLs are poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) for the hole injection and either titanium oxide (TiOx)[26] or zinc oxide

---

[a] Institute of Materials for Electronics and Energy Technology (I-MEET), Friedrich-Alexander University Erlangen-Nürnberg, Martensstr. 7, 91058 Erlangen, Germany. E-mail: Ning.Li@fau.de

[b] BASF Schweiz AG, Schwarzwaldallee 215, CH-4002 Basel, Switzerland

[c] Bavarian Center for Applied Energy Research (ZAE Bayern), Haberstr. 2a, 91058 Erlangen, Germany

† Electronic supplementary information (ESI) available: A universal method to form the equivalent ohmic contact for efficient solution-processed organic tandem solar cells. See DOI: 10.1039/c4ta03182b

Organic Electronics 15 (2014) 569–576

Contents lists available at ScienceDirect

Organic Electronics

journal homepage: www.elsevier.com/locate/orgel

Accelerated degradation of Al^{3+} doped ZnO thin films using damp heat test

Ivan Litzov[a,*], Hamed Azimi[a], Gebhard Matt[a], Peter Kubis[a], Tobias Stubhan[a], Georgi Popov[a], Christoph J. Brabec[a,b]

[a] Institute of Materials for Electronics and Energy Technology (i-MEET), Friedrich-Alexander University of Erlangen-Nuremberg, Martensstrasse 7, 91 058 Erlangen, Germany
[b] Bavarian Center for Applied Energy Research (ZAE Bayern), Haberstrasse 2a, 91 058 Erlangen, Germany

ARTICLE INFO

Article history:
Received 18 September 2013
Received in revised form 28 November 2013
Accepted 2 December 2013
Available online 19 December 2013

Keywords:
Aluminum-doped zinc oxide
Work function
Conductivity
Damp heat test

ABSTRACT

Two different types of aluminum-doped zinc oxide (AZO) thin films were fabricated using low cost sol–gel technique. By applying damp heat testing, the optical and electrical properties of those films were investigated under the influence of accelerated degradation from moisture or moisture vapor. Complementary measurements of optical transmittance, work function, and conductivity allowed exploring the degradation of AZO thin films and the corresponding OPV devices. We found that optical properties like transmittance, absorption coefficient, and band gap are not influenced by temperature and moisture. However, an increase in the work function, and a decrease in the conductivity of AZO films were observed upon damp heat exposure indicating the formation of a barrier or depletion layer at the metal oxide semiconductor interface.

1. Introduction

In the last three decades, metal oxides (MeOx) have been successfully used in applications such as organic photovoltaic cells (OPVs) [8,11,15,17,18,20,21,23,27,29–32], organic light emitting diodes (OLEDs) [28], and thin film transistors (TFTs) [10,17].

Today various organic bulk heterojunction (BHJ) solar cells architectures have been established, such as the normal [15,16,18], the inverted [21,22,27,31] and the tandem solar cell structure [29,30,32]. These strategies led to steadily improving the efficiency of organic solar cells. In comparison to the BHJ solar cells with normal geometry, the inverted BHJ solar cells could provide superior device stability without compromising the device efficiency. In order to design efficient BHJ solar cells, the well-established MeOx interface materials are requested to provide not only excellent optical and electrical properties, but also outstanding environmental stability. From the standpoint of device stability, the electrical contact of TCO layers to the less air sensitive high work function metals such as Ag or Au is of high importance [8,21,22,25].

Many research groups have been able to synthesize TCO materials such as intrinsic ZnO (i-ZnO) or Al^{3+} doped ZnO (AZO) that were successfully applied as an interfacial layer in the normal and inverted BHJ solar cells [8,11,15,21–23,29,31]. Most of these synthesis routes are based on precursor solutions or the classical synthesis pathways, which belong to the class of sol–gel process.

In order to develop stable inverted organic BHJ solar cells with high device efficiencies, degradation mechanisms in organic BHJ solar cells have been intensively investigated [6,11,12,14,27]. These studies have mainly focused on the fundamental degradation mechanisms of the organic semiconductor layer. For a better understanding of the degradation mechanisms, more studies with particular emphasis on, the degradation of the MeOx layers are needed.

---

* Corresponding author. Tel.: +49 (0)9131 (85) 27722; fax: +49 (0)9131/85 28495.
E-mail address: ivan.litzov@ww.uni-erlangen.de (I. Litzov).

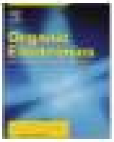
1566-1199/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.orgel.2013.12.001

Organic Electronics 15 (2014) 3800–3804

Contents lists available at ScienceDirect

Organic Electronics

journal homepage: www.elsevier.com/locate/orgel



Letter

A new dithienosilole-based oligothiophene with methyldicyanovinyl groups for high performance solution-processed organic solar cells

Yuriy N. Luponosov[a,*,1], Jie Min[b,*,1], Tayebeh Ameri[b], Christoph J. Brabec[b,c], Sergei A. Ponomarenko[a,d]

[a] Enikolopov Institute of Synthetic Polymeric Materials of the Russian Academy of Sciences, Profsoyuznaya st. 70, Moscow 117393, Russia
[b] Institute of Materials for Electronics and Energy Technology (I-MEET), Friedrich-Alexander-University Erlangen-Nuremberg, Martensstraße 7, 91058 Erlangen, Germany
[c] Bavarian Center for Applied Energy Research (ZAE Bayern), Haberstraße 2a, 91058 Erlangen, Germany
[d] Chemistry Department, Moscow State University, Leninskie Gory 1-3, Moscow 119991, Russia

ARTICLE INFO

Article history:
Received 11 August 2014
Received in revised form 5 September 2014
Accepted 5 September 2014
Available online 18 September 2014

Keywords:
Oligothiophene
Donor–acceptor oligomer
Organic solar cell
Small molecule
Dicyanovinyl groups

ABSTRACT

A new linear dithienosilole-based oligothiophene end-capped with methyl and electron-withdrawing dicyanovinyl groups, **DTS(Oct)$_2$-(2T-DCV-Me)$_2$**, was prepared in good yield. This oligomer exhibited broad absorption spectra in bulk down to the near-IR region with the optical edge at 900 nm, resulting in an initially high power conversion efficiency of 5.44% in solution-processed organic solar cells using PC$_{71}$BM as an acceptor.

1. Introduction

Organic solar cell technology is a promising candidate for the solar energy conversion compared to its inorganic counterparts due to its low cost, light weight, and potential use in flexible devices [1]. Solution-processed bulk heterojunction organic solar cells (BHJ OSCs) possess potential for commercialization because of their high internal quantum efficiency and possibility to use large-scale printing techniques [2]. Today the most efficient organic solar cells (OSCs) based on polymer donor (D) and fullerene derivative acceptor (A) achieve power conversion efficiencies (PCEs) over 10% both in single and tandem solar cells [3]. However polymers suffer from difficult purifications, broad molecular weight distributions, and batch to batch variations. In a parallel effort, OSCs based on small molecules have attracted extensive attention due to easy mass-scale production, well-defined molecular structures, definite molecular weights, easily controlled high purity and well photovoltaic performance reproducibility [4].

Valuable insight into the design of oligomers for organic photovoltaics was given by the work of Bäuerle et al., who have introduced the A–D–A strategy and used oligothiophene fragments as donor units and dicyanovinyl (DCV) groups as terminal acceptor units [5]. Chen et al. significantly extended design of donor–acceptor oligomers and used dithienosilole [6] or benzodithiophene [7] as central donor blocks and alkyl cyanoacetate [6,8] or rhodanine as acceptor groups [9]. Bazan et al. introduced D1–A–D2–A–D1

---

* Corresponding authors.
E-mail addresses: luponosov@ispm.ru (Y.N. Luponosov), min.jie@ww.uni-erlangen.de (J. Min).

[1] Yu. N. Luponosov and J. Min contributed equally.

http://dx.doi.org/10.1016/j.orgel.2014.09.030

Energy &
Environmental
Science

ANALYSIS

View Article Online
View Journal | View Issue

Cite this: Energy Environ. Sci., 2014, 7, 2792

Cost analysis of roll-to-roll fabricated ITO free single and tandem organic solar modules based on data from manufacture†

Florian Machui,[a*] Markus Hösel,[b] Ning Li,[a] George D. Spyropoulos,[a] Tayebeh Ameri,[a] Roar R. Søndergaard,[b] Mikkel Jørgensen,[b] Arnulf Scheel,[c] Detlef Gaiser,[c] Kilian Kreul,[d] Daniel Lenssen,[d] Mathilde Legros,[e] Noella Lemaitre,[e] Marja Vilkman,[f] Marja Välimäki,[f] Sirpa Nordman,[f] Christoph J. Brabec[a] and Frederik C. Krebs[b*]

We present a cost analysis based on state of the art printing and coating processes to fully encapsulated, flexible ITO- and vacuum-free polymer solar cell modules. Manufacturing data for both single junctions and tandem junctions are presented and analyzed. Within this calculation the most expensive layers and processing steps are identified. Based on large roll-to-roll coating experiments the exact material consumptions were determined. In addition to the data for the pilot scale experiment presented here, projections to medium and large scale scenarios serve as a guide to achieve cost targets of 5 €ct per W_p in a detailed material and cost analysis. These scenarios include the replacement of cost intensive layers as well as process optimization steps. Furthermore, the cost structures for single and tandem devices are listed in detail and discussed. In an optimized model the material costs drop below 10 € per m^2 which proves that OPV is a competitive alternative to established power generation technologies.

Received 17th April 2014
Accepted 3rd June 2014

DOI: 10.1039/c4ee01222d

www.rsc.org/ees

Broader context

Among the emerging solar cell technologies organic photovoltaics (OPVs) have gained enormous attention due to their various advantages in applications, i.e. light weight, semitransparency, tunable band gaps and colors. The decisive criteria for a market entrance of a new renewable technology to become a successful competitor are the costs and cost potential which are influenced by their processing technique. Currently processing of photovoltaic devices is mainly done in non-continuous batch-to-batch processes at elevated temperatures. OPVs offer the advantage of high throughput due to their compatibility to continuous roll-to-roll coating techniques. This leads to the potential to dramatically reduce the processing costs in comparison to mature photovoltaic technologies. One of the drawbacks of OPVs is their lower device efficiency in comparison to inorganic materials. The use of tandem devices offers the potential to overcome the limiting device efficiency of OPVs which requires the printing of several additional layers. Based on state of the art processing costs the exact material consumptions for single and tandem devices were determined and compared. We demonstrate that OPV is a competitive energy technology which is not only competitive with inorganic PV, but also with other energy technologies such as wind, hydro and biomass.

1. Introduction

An increasing world population combined with increasing living standards intensifies the demand for low cost, clean and renewable energy sources. Due to air pollution and carbon dioxide emissions from combustion of fossil fuels the need for regenerative energy sources is becoming a compelling necessity. Organic solar cells (OSCs) are often discussed as an alternative to inorganic photovoltaics, due to their advantages of light weight, flexible substrates and tunable band gaps. However, the most persuasive reason is the promise of a low cost technology, competitive to silicon and thin layer products. The cost potential of organic photovoltaics (OPVs) originates from the low temperature and solution based processing which enables the use of roll-to-roll (R2R) based production methods at high speed and high throughput. Different film application techniques have been demonstrated which can be used in a R2R

---

[a] Materials for Electronics and Energy Technology (i-MEET), Department of Material Science and Engineering, Friedrich-Alexander University Erlangen-Nürnberg, Martensstrasse 7, 91058 Erlangen, Germany. E-mail: florian.machui@ww.uni-erlangen.de; Fax: +49 (0)9131 85-28495; Tel: +49 (0)9131 85-27727

[b] Department of Energy Conversion and Storage, Technical University of Denmark, Frederiksborgvej 399, DK-4000 Roskilde, Denmark

[c] Heraeus Precious Metals GmbH & Co. KG, Electronic Materials Division, Chempark Leverkusen Bldg. B202, 51368 Leverkusen, Germany

[d] DELO Industrial Adhesives, DELO-Allee 1, 86949 Windach, Germany

[e] CEA, LITEN, INES Campus, F-73375 Le Bourget du Lac, France

[f] VTT Technical Research Centre of Finland, Printed and hybrid functionalities, P.O.Box 1000, FI-02044 VTT, Finland

† Electronic supplementary information (ESI) available. See DOI: 10.1039/c4ee01222d

Solar Energy Materials & Solar Cells 128 (2014) 441–446

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Large area slot-die coated organic solar cells on flexible substrates with non-halogenated solution formulations

Florian Machui[a,*,1], Luca Lucera[1,b], George D. Spyropoulos[a], Johann Cordero[a], Abid S. Ali[a], Peter Kubis[a], Tayebeh Ameri[a], Monika M. Voigt[a,b], Christoph J. Brabec[a,b]

[a] Institute Materials for Electronics and Energy Technology (i-MEET), Department of Material Science and Engineering, Friedrich-Alexander University of Erlangen-Nuremberg, Martensstrasse 7, 91058 Erlangen, Germany
[b] Bavarian Center of Applied Energy Research (ZAE Bayern), Haberstrasse 2a, 91058 Erlangen, Germany

A R T I C L E I N F O

Article history:
Received 9 December 2013
Received in revised form
30 May 2014
Accepted 5 June 2014
Available online 1 July 2014

Keywords:
Organic photovoltaics
Slot-die coating
Ink formulation
Film homogeneity
Flexible substrates
Solvent

A B S T R A C T

The transfer from lab scale to industrial application is one of the challenges for organic photovoltaics. For this, non-halogenated formulations are a decisive need for the upscaling process, as are roll-to-roll (R2R) compatible methods. Devices processed with o-xylene using slot-die coating as a sheet-to-sheet technique show a reduced efficiency on a larger scale compared to lab scale solar cells. By using a mixture of high and low volatile solvents which selectively dissolve one component, the film homogeneity and the efficiency is dramatically improved. The slot-die coated active layers for solar cells processed from non-halogenated solvents show device efficiencies above 3% on flexible substrates.

1. Introduction

Printed, organic solar cells gained considerable academic and industrial attention offering the advantages of a cost-effective and highly efficient technology, which is a promising candidate to compensate the rising worldwide energy demand [1,2]. Solution processed polymer solar cells are currently reaching efficiencies over 10% and are on their way to proof the feasibility of the predicted efficiencies of 15–20% by Dennler et al. and Li et al. [3–5]. Compared to their inorganic counterparts organic solar cells offer the advantage of a low temperature, solution processable technique. The active layer of organic solar cells consists in most of the cases of a bulk-heterojunction (BHJ), an interpenetrating network of a donor and an acceptor material. Commonly used materials are poly(3-hexylthiophene-2,5-diyl) and [6,6]-phenyl-C61-butyric acid methyl ester (P3HT:PCBM) as donor and acceptor, respectively. Generally, best device efficiencies can be achieved with halogenated, aromatic solvents, i.e. chlorobenzene (CB) and ortho-dichlorobenzene (DCB) [6]. Due to their toxicity and their harmful impact on the environment, these solvents are not suitable for industrial manufacturing since this would lead to an increased expense for additional personal protection equipment and containments. Often mentioned alternative solvents are o-xylene, toluene and tetrahydronaphthalene (THN) [6–8]. Compared to halogenated solvents, the solubility for most materials in these solvents is lower. When toluene is used, a cluster formation is observed which is not beneficial for the charge transfer process and therefore for the device efficiency [9,10]. Nevertheless it has been shown that o-xylene can be used for device fabrication resulting in comparable efficiencies [11,12]. One drawback of o-xylene as solvent is the P3HT agglomeration and the tendency to form gels which can lead to clogging of the coating equipment [13,14].

Lange et al. used different solvent and solvent blends for inkjet printed devices with an amorphous polymer in the active layer [15]. The poly[9,9-dioctylfluorenyl-2,7-diyl-co-(10,12-bis(thiophen-2-yl)-3,6-dioxooctyl-11-thia-9,13-diaza-cyclopenta[b]triphenylene)] (PFDTBTP):PCBM solar cells showed a 3.5% power conversion efficiency when inkjet printed from chlorobenzene/trichlorobenzene solutions and led to efficiencies below 3% when processed from anisole/THN, p-xylene/THN and p-xylene/mesitylene/THN mixtures. A coarser phase separation and pinholes were found for the devices processed with the non-halogenated solutions compared to the use of chlorinated solvents. Vanlaeke et al. and Zimmermann et al. showed P3HT:PCBM device with efficiencies above 3% spin-coated from THN solutions on ITO glass [7,8].

The most used method for processing of organic solar cells is spin-coating, since it requires only few formulation efforts and homogeneous films can be fabricated with a high reproducibility

---

* Corresponding author. Tel.: +49 9131 85 27711; fax: +49 9131 85 28495.
E-mail address: florian.machui@ww.uni-erlangen.de (F. Machui).
URL: http://www.i-meet.ww.uni-erlangen.de/ (F. Machui).

[1] These two authors have contributed equally to this work.

http://dx.doi.org/10.1016/j.solmat.2014.06.011

Journal of
Materials Chemistry C

PAPER

View Article Online
View Journal | View Issue

Cite this: J. Mater. Chem. C, 2014, 2, 7614

A star-shaped D–π–A small molecule based on a tris(2-methoxyphenyl)amine core for highly efficient solution-processed organic solar cells†

Jie Min,*[a] Yuriy N. Luponosov,[b] Alexander N. Solodukhin,[b] Nina Kausch-Busies,[c] Sergei A. Ponomarenko,[bd] Tayebeh Ameri[a] and Christoph J. Brabec*[ae]

Received 15th June 2014
Accepted 11th July 2014

DOI: 10.1039/c4tc01277a

www.rsc.org/MaterialsC

A new star-shaped D–π–A small molecule, 2,2′,2″-(nitrilotris(3-methoxy-4,1-phenylene)-2,2′-bithiene-5′,5-diyleth-1-yl-1-ylidene))trimalononitrile **N(PhOMe)-2T-DCN-Me)$_3$**, with high efficiency potential for photovoltaic applications was synthesized. Introducing a soluble tris(2-methoxyphenyl)amine (TPA-MeO) core unit can significantly improve the solubility of star-shaped small molecules without negatively impacting intramolecular conjugation and intermolecular solid state arrangements. Solution-processed organic solar cells based on a blend of **N(PhOMe-2T-DCN-Me)$_3$** and PC$_{71}$BM show an initially high power conversion efficiency of over 4% under simulated AM 1.5.

Introduction

The dynamic development in solution-processed small molecule organic solar cells (OSCs) has recently led to high power conversion efficiencies (PCEs) of >8% approaching those of polymer-based devices with the most promising bulk heterojunction (BHJ) architecture.[1-3] Compared to their polymeric counterparts, structurally well-defined small molecules avoid the inherent batch-to-batch variations of physical properties and therefore provide higher reproducibility.[4,5] The current research pursuits for small molecule-based OSCs target even higher efficiencies by designing and synthesizing new organic small molecules, such as star- or X-shaped molecules and[6-10] one- or two-dimensional oligomers with D–A–D or A–D–A structures.[1,11-13] In particular, the most promising organic small molecule donor materials for photovoltaic applications are normally built by connecting various electron donating (donor) and electron capturing (acceptor) moieties through a π-conjugating spacer (D–π–A).[7,8,12-16] Such a D–π–A structure can be used to lower the optical band gap to broaden molecular optical absorption and to assist the formation of favorable morphologies for high photovoltaic performance.[7] A large number of D–π–A small molecules have been extensively studied and exhibit considerable molecular photovoltaic properties. For instance, Li *et al.* and Chen *et al.* synthesized two two-dimensional small molecules, H2 and DR3TBDTT with an A–π–D–π–A framework which show excellent photovoltaic performance with PCEs of up to 6.75% and 8.12%, respectively.[2,17] Bazan and his co-workers synthesized a promising linear molecule, DTS(FBTTh$_2$)$_2$, with a high PCE up to 7%,[18] and then introduced an optical spacer (ZnO) between the aluminum cathode and the photoactive layers to further improve the PCE.[19] More recently, using a two-dimensional conjugated small molecule (SMPV1), the best PCE of OSCs reached 8% for single junction solar cells, and 10% for double-junction tandem OSCs,[20] endowing organic small molecules with a great application potential for the generation of low cost solar cells.

However, compared to π-conjugated polymers, the relatively short conjugated backbone of D–π–A linear small molecules reduces the tendency for the formation of interpenetrating networks and mixed morphologies when blended with fullerene derivatives.[21] The limited conjugation length also makes charge transport in these materials primarily intermolecular with a negligible intramolecular component, which increases charge recombination in OSCs.[22] In addition, the dependence of photovoltaic performance on the spin-coated processing system further limits the applications of these materials in roll-to-roll processed flexible photovoltaic devices. Overcoming these obstacles requires enhancing intramolecular π–π stacking interactions, facilitating charge transport and forming a process-insensitive morphology in OSCs, as well as further increasing the PCE. A promising approach is to incorporate

---

[a] Institute of Materials for Electronics and Energy Technology (I-MEET), Friedrich-Alexander-University Erlangen-Nuremberg, Martensstraße 7, 91058 Erlangen, Germany. E-mail: jie.min@ww.uni-erlangen.de

[b] Enikolopov Institute of Synthetic Polymeric Materials of the Russian Academy of Sciences, Profsoyuznaya st. 70, Moscow 117393, Russia

[c] Heraeus Precious Metals GmbH & Co. KG, Conductive Polymers Division (Clevios), Chempark Leverkusen Build. B202, D-51368 Leverkusen, Germany

[d] Chemistry Department, Moscow State University, Leninskie Gory 1-3, Moscow 119991, Russia

[e] Bavarian Centre for Applied Energy Research (ZAE Bayern), Haberstraße 2a, 91058 Erlangen, Germany

† Electronic supplementary information (ESI) available: TGA and DSC plots, *J–V* curves of OSCs with various D : A ratios, and ^{1}H and ^{13}C NMR spectra of monomers. See DOI: 10.1039/c4tc01277a

Materials Views
www.MaterialsViews.com

ADVANCED ENERGY MATERIALS
www.advenergymat.de

Alkyl Chain Engineering of Solution-Processable Star-Shaped Molecules for High-Performance Organic Solar Cells

Jie Min, Yuriy N. Luponosov, Andreas Gerl, Marina S. Polinskaya, Svetlana M. Peregudova, Petr V. Dmitryakov, Artem V. Bakirov, Maxim A. Shcherbina, Sergei N. Chvalun, Souren Grigorian, Nina Kaush-Busies, Sergei A. Ponomarenko, Tayebeh Ameri, and Christoph J. Brabec*

The impact of alkyl side-chain substituents on conjugated polymers on the photovoltaic properties of bulk heterojunction (BHJ) solar cells has been studied extensively, but their impact on small molecules has not received adequate attention. To reveal the effect of side chains, a series of star-shaped molecules based on a triphenylamine (TPA) core, bithiophene, and dicyanovinyl units derivatized with various alkyl end-capping groups of methyl, ethyl, hexyl and dodecyl is synthesized and studied to comprehensively investigate structure-properties relationships. UV-vis absorption and cyclic voltammetry data show that variations of alkyl chain length have little influence on the absorption and highest occupied molecular orbital (HOMO)-lowest unoccupied molecular orbital (LUMO) levels. However, these seemingly negligible changes have a pronounced impact on the morphology of BHJ thin films as well as their charge carrier separation and transportation, which in turn influences the photovoltaic properties of these small-molecule-based BHJ devices. Solution-processed organic solar cells (OSCs) based on the small molecule with the shortest methyl end groups exhibit high short circuit current (J_{sc}) and fill factor (FF), with an efficiency as high as 4.76% without any post-treatments; these are among the highest reported for solution-processed OSCs based on star-shaped molecules.

1. Introduction

Bulk heterojunction (BHJ) organic solar cells (OSCs) based on small molecules as donor materials have attracted extensive attention due to their numerous advantages, which include well-defined molecular structure, easy purification, easy mass-scale production, high charge carrier mobility, and better batch-to-batch reproducibility.[1–4] Recently, the power conversion efficiency (PCE) of the solution-processed small molecule (SM) OSCs has reached 7–8% via designing novel linear small molecules.[5–8] Most of small molecules as donor materials for photovoltaic applications normally contains four key constituent components: donor/acceptor (D/A) units, conjugated bridges, heteroatom substitutions, and side-chains. The creative design and choice of donor or acceptor units, conjugated bridges, and heteroatom substitutions has been successfully conquered the shortcomings

---

J. Min, A. Gerl, T. Ameri, C. J. Brabec
Institute of Materials for Electronics and
Energy Technology (I-MEET)
Friedrich-Alexander-University Erlangen-Nuremberg
Martensstraße 7, 91058, Erlangen, Germany
E-mail: Min.jie@ww.uni-erlangen.de
Y. N. Luponosov, M. S. Polinskaya, P. V. Dmitryakov, A. V. Bakirov,
M. A. Shcherbina, S. N. Chvalun, S. A. Ponomarenko
Enikolopov Institute of Synthetic Polymeric Materials
of the Russian Academy of Sciences
Profsoyuznaya st. 70, Moscow, 117393, Russia
S. M. Peregudova
Nesmeyanov Institute of Organoelement Compounds
Russian Academy of Sciences
Vavilova St. 28, Moscow, 119991, Russia

S. Grigorian
Institute of Physics
University of Siegen
Emmy-Noether-Campus
Walter-Flex-Str. 3, D-57068, Siegen, Germany
N. Kaush-Busies
Heraeus Precious Metals GmbH & Co. KG
Conductive Polymers Division (Clevios)
Chempark Leverkusen Build. B202, D-51368, Leverkusen, Germany
S. A. Ponomarenko
Chemistry Department
Moscow State University
Leninskie Gory 1-1, Moscow, 119991, Russia
C. J. Brabec
Bavarian Center for Applied Energy Research (ZAE Bayern)
Haberstraße 2a, 91058, Erlangen, Germany

DOI: 10.1002/aenm.201301234

Adv. Energy Mater. 2014,
DOI: 10.1002/aenm.201301234

Journal of
Materials Chemistry A

PAPER

View Article Online
View Journal | View Issue

Cite this: J. Mater. Chem. A, 2014, 2, 16135

Effects of oligothiophene π-bridge length on physical and photovoltaic properties of star-shaped molecules for bulk heterojunction solar cells†

Jie Min,*[a] Yuriy N. Luponosov,[b] Derya Baran,[a] Sergei N. Chvalun,[bc]
Maxim A. Shcherbina,[bcd] Artem V. Bakirov,[bc] Petr V. Dmitryakov,[c]
Svetlana M. Peregudova,[e] Nina Kausch-Busies,[f] Sergei A. Ponomarenko,[bg]
Tayebeh Ameri[a] and Christoph J. Brabec[ah]

Received 18th April 2014
Accepted 7th June 2014

DOI: 10.1039/c4ta01933d

www.rsc.org/MaterialsA

The preparation of four different star-shaped donor (D)–π–acceptor (A) small molecules (**N(Ph-1T-DCN-Me)$_3$**, **N(Ph-2T-DCN-Me)$_3$**, **N(Ph-2T-DCN-Hex)$_3$** and **N(Ph-3T-DCN-Hex)$_3$**) possessing various oligothiophene π-bridge lengths and their use in solution-processed bulk heterojunction small molecule solar cells is reported. Optical and electrochemical data show that increasing oligothiophene π-bridge length leads to a decrease of the optical band gap due to a parallel increase of the highest occupied molecular orbital (HOMO) level. Furthermore, subtle modifications of a molecular π-bridge length strongly affect the thermal behavior, solubility, crystallization, film morphology and charge carrier mobility, which in turn significantly change the device performance. Although the moderately increasing oligothiophene π-bridge length uplifts the HOMO level, it nevertheless induces an increase of the efficiency of the resulting solar cells due to a simultaneous improvement of the short circuit current (J_{sc}) and fill factor (FF). The study demonstrates that such an approach can represent an interesting tool for the effective modulation of the photovoltaic properties of the organic solar cells (OSCs) at a moderate cost.

1. Introduction

During the last decade, bulk heterojunction (BHJ) organic solar cells (OSCs) utilizing conjugated polymers or small molecules have attracted attention due to the low fabrication costs achievable via solution-processing methods.[1–4] In particular, intensive research on small molecule OSCs has been carried out resulting in a remarkable improvement of the photovoltaic performance by judicious molecular design, morphology control and device optimization.[5–7] They are emerging as promising substitutes for conjugated polymers owing to the advantages of simple synthesis, definite molecular structure and weight, high purity, and reproducible photovoltaic performance.[8] The current research is focused on obtaining high molecular physical and photovoltaic properties by the design and synthesis of novel push–pull molecular systems built by connecting various electron donating (donor) and electron capturing (acceptor) moieties through a π-conjugating spacer (D–π–A). Such an approach can be used to lower the optical band gap to broaden molecular optical absorption and assist the formation of favorable morphologies for high photovoltaic performance.[9] It is also apparent that desirable highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) levels can be obtained by coupling a wide variety of donor and acceptor units.[10] A large number of D–A small molecules, such as linear molecules,[5,6,8–11,13–17] star-shaped molecules[12,18–24] and other organic dyes,[25] have been extensively studied and exhibited considerable molecular photovoltaic properties. More recently, using this class of compounds, the best power conversion efficiency (PCE) of OSCs reached 8% for single junction solar cells,[5,13] and 10% for double-junction

---

[a] Institute of Materials for Electronics and Energy Technology (i-MEET), Friedrich-Alexander-University Erlangen-Nuremberg, Martensstraße 7, 91058 Erlangen, Germany. E-mail: Min.Jie@ww.uni-erlangen.de

[b] Enikolopov Institute of Synthetic Polymeric Materials of the Russian Academy of Sciences, Profsoyuznaya st. 70, Moscow 117393, Russia

[c] Scientific and Research Centre "Kurchatov Institute", 1 Kurchatov square, Moscow 123182, Russia

[d] Moscow Institute of Physics and Technology, 9 Institutskiy line, Dolgoprudny, Moscow region, 141700, Russia

[e] Nesmeyanov Institute of Organoelement Compounds, Russian Academy of Sciences, Vavilova St. 28, Moscow 119991, Russia

[f] Heraeus Precious Metals GmbH & Co. KG, Conductive Polymers Division (Clevios), Chempark Leverkusen Build. B202, D-51368 Leverkusen, Germany

[g] Chemistry Department, Moscow State University, Leninskie Gory 1-3, Moscow 119991, Russia

[h] Bavarian Center for Applied Energy Research (ZAE Bayern), Haberstraße 2a, 91058 Erlangen, Germany

† Electronic supplementary information (ESI) available: Material synthesis, ^{1}H and ^{13}C NMR spectra of monomers, TGA and DSC plots, CV curves, XRD data and hole mobilities measurements of pristine and blended films. See DOI: 10.1039/c4ta01933d

Materials Views
www.MaterialsViews.com

ADVANCED ENERGY MATERIALS
www.advenergymat.de

Interface Design to Improve the Performance and Stability of Solution-Processed Small-Molecule Conventional Solar Cells

Jie Min, Yuriy N. Luponosov, Zhi-Guo Zhang, Sergei A. Ponomarenko, Tayebeh Ameri, Yongfang Li, and Christoph J. Brabec**

A systematic study on the effect of various cathode buffer layers on the performance and stability of solution-processed small-molecule organic solar cells (SMOSCs) based on tris{4-[5-(1,1-dicyanobut-1-en-2-yl)-2,2-bithiophen-5-yl]phenyl}amine (N(Ph-2T-DCN-Et)$_3$):6,6-phenyl-C71-butyric acid methyl ester (N(Ph-2T-DCN-Et)$_3$:PC$_{70}$BM) is presented. The power conversion efficiency (PCE) in these systems can be significantly improved from approximately 4% to 5.16% by inserting a metal oxide (ZnO) layer between the active layer and the Al cathode instead of an air-sensitive Ba or Ca layer. However, the low work-function Al cathode is susceptible to chemical oxidation in the atmosphere. Here, an amine group functionalized fullerene complex (DMAPA-C$_{60}$) is inserted as a cathode buffer layer to successfully modify the interface towards ZnO/Ag and active layer/Ag functionality. For devices with ZnO/DMAPA-C$_{60}$/Ag and DMAPA-C$_{60}$/Ag cathodes the PCEs are improved from 2.75% to 4.31% and to 5.40%, respectively, compared to a ZnO/Ag device. Recombination mechanisms and stability aspects of devices with various cathodes are also investigated. The significant improvement in device performance and stability and the simplicity of fabrication by solution processing suggest this DMAPA-C$_{60}$-based interface as a promising and practical pathway for developing efficient, stable, and roll-to-roll processable SMOSCs.

1. Introduction

The dynamic development in solution-processed small-molecule organic solar cells (SMOSCs) has recently led to high power conversion efficiencies (PCEs) of >8% approaching those of polymer-based devices with the most promising bulk heterojunction (BHJ) architecture.[1–3] For commercial application, structurally well-defined small molecules offer relatively simple synthesis and purification, avoid the inherent batch-to-batch variations, and provide higher reproducibility as compared to their polymeric counterparts.[4–6] However, for a widespread deployment of OSCs as large-area, rooftop applications for residential and commercial buildings, high module efficiencies >10% and lifetimes >10 years are required.[7] To achieve these performance goals based on SMOSCs (mainly their efficiencies and stabilities), different ways have been explored including i) designing new light-harvesting materials[4,8–10] and ii) proposing more efficient devices and stable device architectures.[11–13]

In most cases, SMOSCs based on a conventional device architecture are similar to polymer OSCs, which are fabricated by sandwiching a photoactive layer between a metal cathode (e.g., Al, Ca/Al) and a transparent indium tin oxide (ITO) anode with a poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS) anode buffer layer.[13] However, long-term stability of these devices in ambient conditions is a major concern. The commonly used low work function cathode interlayers, calcium (Ca) and barium (Ba), are very sensitive to moisture and oxygen that often causes the formation of detrimental quenching sites at areas near the interface between the active layer and the cathode. Metal ions formed at the interface tend to migrate into the active layer and form an unstable cathode contact thus further affecting the efficiency and long-term stability of these devices.[14] In addition, chemical oxidation of the low work function Al electrode is another reason for short device durability.[15] To overcome the stability issues of the conventional solar cells, one way is to use an inverted architecture SMOSCs.[16,17] Recently, we successfully constructed efficient small molecule inverted solar cells by employing a combination of aluminum-doped ZnO (AZO)

J. Min, Dr. T. Ameri, Prof. C. J. Brabec
Institute of Materials for Electronics and
Energy Technology (I-MEET)
Friedrich-Alexander University Erlangen-Nuremberg
Martensstraße 7, 91058 Erlangen, Germany
E-mail: Min.jie@ww.uni-erlangen.de;
christoph.brabec@ww.uni-erlangen.de
Dr. Y. N. Luponosov, Prof. S. A. Ponomarenko
Enikolopov Institute of Synthetic Polymeric Materials of the Russian
Academy of Sciences
Profsoyuznaya St. 70, Moscow 117393, Russia
Dr. Z.-G. Zhang, Prof. Y. Li
CAS Key Laboratory of Organic Solids
Institute of Chemistry
Chinese Academy of Sciences
Beijing 100190, China
Prof. S. A. Ponomarenko
Chemistry Department
Moscow State University
Leninskie Gory 1–3, Moscow 119991, Russia
Prof. C. J. Brabec
Bavarian Center for Applied Energy Research (ZAE Bayern)
Haberstraße 2a, 91058 Erlangen, Germany

DOI: 10.1002/aenm.201400816

Eur. Phys. J. B (2014) 87: 58
DOI: 10.1140/epjb/e2014-41100-1

THE EUROPEAN
PHYSICAL JOURNAL B

Colloquium

Advances in wide bandgap SiC for optoelectronics

Haiyan Ou[1,a], Yiyu Ou[1,b], Aikaterini Argyraki[1], Saskia Schimmel[2], Michl Kaiser[2], Peter Wellmann[2], Margareta K. Linnarsson[3], Valdas Jokubavicius[4], Jianwu Sun[4,c], Rickard Liljedahl[4], and Mikael Syväjärvi[4]

[1] Department of Photonics Engineering, Technical University of Denmark, 2800 Lyngby, Denmark
[2] Materials of Electronics Energy Technology, University of Erlangen-Nuremberg, 91058 Erlangen, Germany
[3] School of Information and Communication Technology, KTH Royal Institute of Technology, 16440 Kista, Sweden
[4] Department of Physics, Chemistry and Biology, Linköping University, 58183 Linköping, Sweden

Received 23 December 2013 / Received in final form 21 January 2014

Abstract. Silicon carbide (SiC) has played a key role in power electronics thanks to its unique physical properties like wide bandgap, high breakdown field, etc. During the past decade, SiC is also becoming more and more active in optoelectronics thanks to the progress in materials growth and nanofabrication. This paper will review the advances in fluorescent SiC for white light-emitting diodes, covering the poly-crystalline doped SiC source material growth, single crystalline epitaxy growth of fluorescent SiC, and nanofabrication of SiC to enhance the extraction efficiency for fluorescent SiC based white LEDs.

1 Introduction

Silicon carbide (SiC) is the only group IV compound semiconductor, and it has more than 200 polytypes. Among them the most commonly used are 4H, 6H, 3C and 15R. The wide bandgap makes SiC a very attractive semiconductor to make devices for applications in high power, high frequency and high temperature environment.

In addition to the traditional applications, SiC has been emerging as a promising material for light-emitting diodes (LED) since Satoshi Kamiyama in 2006 found that nitrogen (N) and boron (B) co-doped SiC has very high donor-acceptor pair (DAP) emission efficiency [1].

The LED light sources are deemed to be the future market leader thanks to their energy saving and long lifetime, compared to conventional incandescent lamps and fluorescent tubes. Currently, most white LED light sources available in the market are made by mixture of blue color from a blue GaN LED and yellow color emitted from the phosphor excited by the blue LED, as shown in Figure 1a. However, there is always a tradeoff between high lumen efficiency and high color rendering index (CRI) for this type of light source. The phosphor degrades much faster than the blue LED chip, so the white light turns blue over time. Moreover, phosphor contains rare earth elements, which could be a price bottleneck considering the huge market in future. In order to overcome these limitations and explore the full potential of the white LED light sources, a new type white LED light source based on fluorescent SiC (f-SiC), shown in Figure 1b, has been proposed. Compared to the phosphor based white LED light source, this f-SiC based white light source has a number of advantages: (i) it can have both high efficiency and high color rendering index, opposite to the trade-off observed for phosphor based white LED light sources; (ii) it has even longer lifetime due to the monolithic semiconductor structure; (iii) it has simpler thermal management because SiC is a very good thermal conductor; and (iv) it does not contain rare-earth elements.

As shown in Figure 1b, the f-SiC based white LED light source uses f-SiC as a substrate, as well as a wavelength converter. It consists of one layer of 200 μm thick N and B co-doped SiC and one layer of 50 μm thick N and aluminium (Al) co-doped SiC. A near ultraviolet (NUV) diode is grown on top of the N and Al co-doped SiC. A mirror is formed on top of the NUV diode and diverts all the light to exit from the f-SiC substrate. Silicon carbide has a refractive index of 2.65 at 590 nm [2], causing most of the emitted light from f-SiC to be totally reflected into the device. In order to enhance the light extraction efficiency, as shown in Figure 1b, moth-eye nanostructures are implemented at the exit surface of the f-SiC to increase the emission efficiency in the whole visible spectral range.

The operational mechanism of the f-SiC based white LED is illustrated in Figure 2.

The high energy NUV photons emitted from the NUV LED excite electrons from the top of the valence band to the bottom of the conduction band. The free electrons in the conduction band and the free holes left in the valence band will occupy the donor level (N) and acceptor levels (Al and B), respectively, obeying the Fermi-Dirac

---

[a] e-mail: haou@fotonik.dtu.dk

[b] *Present address*: Light extraction ApS, Diplomvej 373, 2800 Lyngby, Denmark

[c] *Present address*: IMEC, Kapeldreef 75, 3001 Leuven, Belgium

Faraday Discussions

Cite this: *Faraday Discuss.*, 2014, **174**, 313

PAPER

View Article Online
View Journal | View Issue

Design of donor–acceptor star-shaped oligomers for efficient solution-processible organic photovoltaics†

S. A. Ponomarenko,[*ab] Y. N. Luponosov,[a] J. Min,[c] A. N. Solodukhin,[a] N. M. Surin,[a] M. A. Shcherbina,[a] S. N. Chvalun,[a] T. Ameri[c] and C. Brabec[c]

Received 1st July 2014, Accepted 21st July 2014
DOI: 10.1039/c4fd00142g

This contribution describes recent progress in the design, synthesis and properties of solution-processible star-shaped oligomers and their application in organic photovoltaics. Even though alternative chemistry has been used to design such oligomers, the most successful approach is based on a triphenylamine donor branching center, (oligo)thiophene conjugated spacers and dicyanovinyl acceptor groups. These are mainly amorphous low band-gap organic semiconductors, though crystalline or liquid crystalline ordering can sometimes be realized. It was shown that the solubility, thermal behavior and structure of such molecules in the bulk strongly depend on the presence and position of alkyl groups, as well as on their length. The photovoltaic properties of solution-processed molecules of this type are now approaching 5% which exceeds those of vacuum-sublimed devices. The design rules and future perspectives of this class of organic photovoltaic molecules are discussed.

Introduction

Organic photovoltaics is a fast growing area of science and technology due to possibility to create light weight large area flexible solar cells, which can be produced by low cost printing or roll-to-roll techniques.[1] The technology is based on organic semiconductors, either π-conjugated polymers[3] or small molecules,[4] capable of efficient light absorption in the visible spectral range with the creation of excitons. However, opposite to inorganic solar cells, charge separation in organic solar cells (OSC) leading to a photovoltaic effect takes place on the interface between the electron donor and the electron acceptor organic

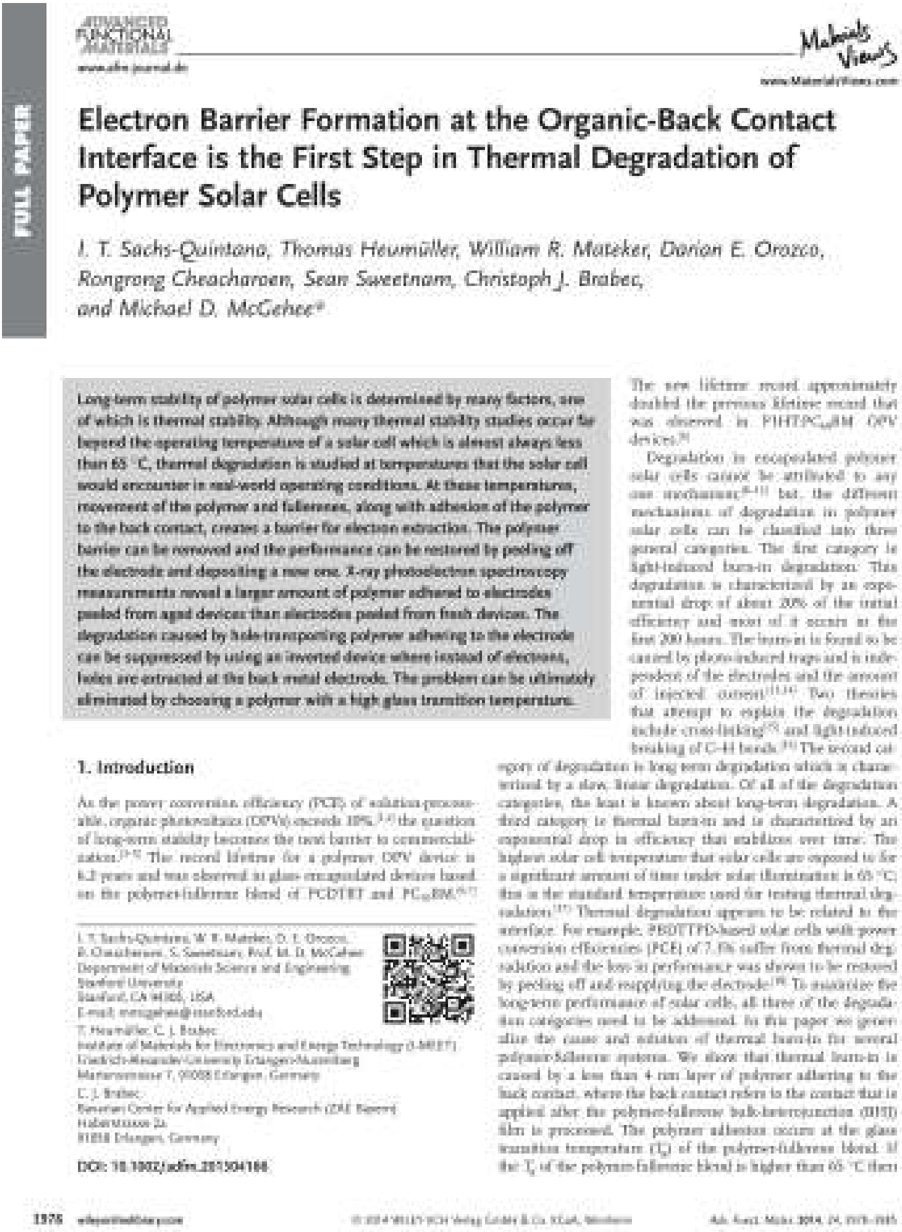
---

[a] *Enikolopov Institute of Synthetic Polymeric Materials of the Russian Academy of Sciences, Profsoyuznaya st. 70, Moscow 117393, Russia. E-mail: ponomarenko@ispm.ru*

[b] *Chemistry Department, Moscow State University, Leninskie Gory 1-3, Moscow 119991, Russia*

[c] *Institute of Materials for Electronics and Energy Technology (I-MEET), Friedrich-Alexander-University Erlangen-Nuremberg, Martensstraße 7, 91058 Erlangen, Germany*

† Electronic supplementary information (ESI) available: ^{1}H NMR spectra and TGA curves. See DOI: 10.1039/c4fd00142g



Electron Barrier Formation at the Organic-Back Contact Interface is the First Step in Thermal Degradation of Polymer Solar Cells

*I. T. Sachs-Quintana, Thomas Heumüller, William R. Mateker, Darian E. Orozco, Rongrong Cheacharoen, Sean Sweetnam, Christoph J. Brabec, and Michael D. McGehee**

Long-term stability of polymer solar cells is determined by many factors, one of which is thermal stability. Although many thermal stability studies occur far beyond the operating temperature of a solar cell which is almost always less than 65 °C, thermal degradation is studied at temperatures that the solar cell would encounter in real-world operating conditions. At these temperatures, movement of the polymer and fullerenes, along with adhesion of the polymer to the back contact, creates a barrier for electron extraction. The polymer barrier can be removed and the performance can be restored by peeling off the electrode and depositing a new one. X-ray photoelectron spectroscopy measurements reveal a larger amount of polymer adhered to electrodes peeled from aged devices than electrodes peeled from fresh devices. The degradation caused by hole-transporting polymer adhering to the electrode can be suppressed by using an inverted device where instead of electrons, holes are extracted at the back metal electrode. The problem can be ultimately eliminated by choosing a polymer with a high glass transition temperature.

1. Introduction

DOI: 10.1002/adfm.201304166

Phys. Status Solidi C **11**, No. 9, 1439–1442 (2014) / **DOI** 10.1002/pssc.201300656

physica status solidi pss c
www.pss-c.com
current topics in solid state physics

Towards X-ray in-situ visualization of ammonothermal crystal growth of nitrides

Saskia Schimmel[*,1], **Ulrike Künecke**[**,1], **Hasan Baser**[2], **Thomas G. Steigerwald**[3], **Benjamin Hertweck**[2], **Nicolas S. A. Alt**[3], **Eberhard Schlücker**[3], **Wilhelm Schwieger**[2], and **Peter Wellmann**[1]

[1] Materials Department 6, University of Erlangen-Nuremberg, Martensstr. 7, 91058 Erlangen, Germany
[2] Institute of Chemical Reaction Engineering, University of Erlangen-Nuremberg, Egerlandstr. 3, 91058 Erlangen, Germany
[3] Institute of Process Machinery and Systems Engineering, University of Erlangen-Nuremberg, Cauerstr. 4, 91058 Erlangen, Germany

Received 8 October 2013, revised 6 January 2014, accepted 18 March 2014

Keywords in-situ X-ray imaging, ammonothermal crystal growth, GaN, nitrides

---

* Corresponding author: e-mail saskia.schimmel@ww.uni-erlangen.de, Phone: +49 9131 85 27719, Fax: +49 9131 85 28495
** e-mail ulrike.kuenecke@ww.uni-erlangen.de, Phone: +49 9131 85 27719, Fax: +49 9131 85 28495

In-situ X-ray visualization of hydrothermal growth of silicalite-1 is applied as an intermediate step for developing X-ray in-situ visualization techniques for ammonothermal growth of nitride materials. In-situ X-ray imaging of silicalite-1 crystals grown by the bulk material dissolution technique (Shimizu and Hamada, Angew. Chem., Int. Ed. **38**, 2725 (1999) [1]) is demonstrated using a stainless steel autoclave equipped with ceramic aluminium oxide windows. Processes in the reaction medium such as local density changes are also visualized. The transferability of the technique to ammonothermal growth of nitrides is evaluated. Furthermore, the applicability of windowless autoclaves for X-ray in-situ monitoring of ammonothermal crystal growth of nitrides is investigated.

1 Introduction Solvothermal processes are usually conducted in closed metal autoclaves which severely complicates obtaining information on the process in-situ. However, in-situ measurements are very advantageous for fundamental understanding as well as process monitoring and control.

Due to the extreme reaction conditions, in-situ measurements during ammonothermal growth of nitride crystals such as gallium nitride (GaN) are particularly challenging and reports on in-situ measurements are scarce so far. Recently, in-situ measurement techniques for UV-Vis spectroscopy as well as video optical measurements have been demonstrated for an ammonothermal reaction medium. While spectroscopic measurements can provide information about intermediate compounds, video optical measurements were used to determine flow direction and velocity by particle imaging. However, video optical measurements suffer from increasing optical absorption with increasing temperature especially above 350 °C [2].

Thus, for measurements of crystal growth rates during ammonothermal growth of e.g. GaN, which typically is conducted in the temperature range of 450 °C to 600 °C [3, 4], in-situ X-ray imaging is very promising. In addition, it may also yield information on source material dissolution similar to its previous application to silicon carbide crystal growth by physical vapour transport [5].

In this work we evaluate the potential of X-ray imaging for in-situ visualization of ammonothermal growth of nitrides. Hydrothermal growth of the zeolite silicalite-1 is applied as an intermediate step. This hydrothermal model system is chosen due to its moderate pressure and temperature requirements compared to ammonothermal growth of GaN which is typically conducted at high pressures of 100 MPa to 300 MPa and temperatures of 450 °C to 600 °C [3, 4]. Making lower demands on the autoclave material allows for using stainless steel instead of the costly and complex to machine nickel base alloy. The low density and low effective atomic number of silicalite-1 ensure that the developed method can easily be transferred to the ammonothermal system since e.g. GaN will be much less challenging with respect to contrast in the X-ray image.

Energy &
Environmental
Science

COMMUNICATION

View Article Online
View Journal | View Issue

Cite this: Energy Environ. Sci., 2014, 7, 3284

Received 27th June 2014
Accepted 29th July 2014

DOI: 10.1039/c4ee02003k

www.rsc.org/ees

Flexible organic tandem solar modules with 6% efficiency: combining roll-to-roll compatible processing with high geometric fill factors†

G. D. Spyropoulos,[ab] P. Kubis,[ab] N. Li,[a] D. Baran,[a] L. Lucera,[a] M. Salvador,[a] T. Ameri,[a] M. M. Voigt,[ac] F. C. Krebs[d] and C. J. Brabec[ab]

Organic solar cell technology bears the potential for high photovoltaic performance combined with truly low-cost, high-volume processing. Here we demonstrate organic tandem solar modules on flexible substrates fabricated by fully roll-to-roll compatible processing at temperatures <70 °C. By using ultrafast laser patterning we considerably reduced the "dead area" of the modules and achieved geometric fill factors beyond 90%. The modules revealed very low interconnection resistance compared to the single tandem cells and exhibited a power conversion efficiency of up to 5.7%. Bending tests performed on the modules suggest high mechanical resilience for this type of device. Our findings inform concrete steps towards high efficiency photovoltaic applications on curved, foldable and moving surfaces.

Broader context

The pressing need for inexpensive carbon-neutral energy sources requires innovative approaches. Organic photovoltaics offers unique opportunities since it uses carbon-based semiconductors, which can be processed from solution and deposited on flexible plastic substrates using high throughput roll-to-roll technologies. This allows for envisioning low-cost, lightweight solar to energy conversion platforms that could find applications in, amongst others, apparel, smart labels, building and car integrated photovoltaics, and moving robots. While roll-to-roll coated organic solar cell modules have been demonstrated in the past, the efficiency of these devices has been rather low, typically not exceeding 2% power conversion efficiency. Here we fabricate and characterize a multicell series stack of organic photovoltaic cells (tandem solar cells) on plastic foil using fully roll-to-roll compatible coating techniques. The solar cells feature a wide spectral response across the solar spectrum. We adopt a concept based on ultrafast laser patterning for dividing the tandem cells into tandem modules. This process enables both high geometrical fill factors and low electrical interconnection losses. As a result, we achieve an unprecedented power conversion efficiency of ~6% for this type of device. Bending tests certify the potential of this type of solar cell for applications that require high mechanical resilience.

Introduction

The pace at which the efficiency of organic photovoltaic devices (OPVs) has been progressing in the last decade allows for envisioning a significant share of this technology in the future energy mix, thereby alleviating the world's increasing energy demand in an environmentally responsible way.[1–3] Crucially, OPVs provide excellent form factors, good performance under indoor lighting conditions and potentially very low energy production costs using solution processable organic semiconductors.[4–7] The combination of these characteristics makes OPVs ideally suited for targeting niche markets that are incompatible with brittle semiconductors, e.g., off-grid portable charging, electronics in apparel and smart labels, as well as building and car integrated photovoltaics for non-planar surfaces,[8,9] while simultaneously enabling production scale-up through roll-to-roll device fabrication.

Despite the recognized potential for high-throughput manufacturing, basic science limitations that have been preventing this technology from market implementation need to be addressed. Particularly, a poor match of the absorption spectrum of the active blend materials with the solar spectrum limits the photon harvesting capabilities and, consequently, the photocurrent generation. Additionally, thermalization losses diminish possible voltage outputs.[10,11] One promising approach for overcoming these limitations is the tandem concept[12–14] sub-cells of different band-gap donor materials are typically combined in series for better matching the absorption of the

---

[a] Institute of Materials for Electronics and Energy Technology (i-MEET), Friedrich-Alexander-University Erlangen-Nuremberg, Martensstraße 7, 91058 Erlangen, Germany. E-mail: George.Spyropoulos@ww.uni-erlangen.de

[b] Bavarian Center for Applied Energy Research (ZAE Bayern), Haberstraße 2a, 91058 Erlangen, Germany

[c] Erlangen Graduate School in Advanced Optical Technologies (SAOT), Paul-Gordan-Str. 6, 91052 Erlangen, Germany

[d] Department of Energy Conversion and Storage, Technical University of Denmark, Frederiksborgvej 399, DK-4000 Roskilde, Denmark

† Electronic supplementary information (ESI) available. See DOI: 10.1039/c4ee02003k

Morphology Related Photodegradation of Low-Band-Gap Polymer Blends

Xiao Wang, Hans-Joachim Egelhaaf, Hans-Georg Mack, Hamed Azimi, Christoph J. Brabec, Alfred J. Meixner, and Dai Zhang**

The morphology related photodegradation of low band-gap polymer blends is investigated using optical microscopy and scanning probe microscopy. Poly[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):[6,6]-phenyl C61-butyric acid methyl ester (PCBM) blend films without and with ODT, as well as poly[(4,40-bis(2-ethylhexyl)dithieno[3,2-b:20,30-d]silole)-2,6-diyl-alt-(2,1,3-benzothiadiazole)-4,7-diyl] (Si-PCPDTBT):PCBM blend films exposed to a focused 632.8 nm laser under ambient condition with and without inert gas protection are studied. The photodegradation of the polymer starts in the vicinity of the PCBM molecules (first sphere degradation), which effectively blocks the electron transfer processes. Stern-Volmer type kinetics are observed in the C-PCPDTBT:PCBM blend with ODT, which indicates that only a small number of photo-oxidized monomer units act as quenchers of the C-PCPDTBT polymer luminescence. Furthermore, in addition to the permanent damage of the polymer molecules, as witnessed from their Raman intensity decrease, the polymer photoluminescence demonstrates partial reversible recovery when inert gas protection is resumed, indicating the involvement of temporary polymer/O_2-charge transfer complexes in the photodegradation process.

1. Introduction

Low band gap polymers provide special opportunities to achieve high power conversion efficiencies of polymer:fullerene organic solar cells because of their wide absorption range.[1–3] Poly[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), a low band gap polymer, has been successfully utilized as electron donor for polymer:fullerene solar cells.[1,4] However, due to the lack of sufficient phase separation of the donor and acceptor,[5,6] solar cells based on the as-cast blend of C-PCPDTBT and fullerene derivatives [6,6]-phenyl C_{61}-butyric acid methyl ester (PCBM) or [6,6]-phenyl C_{71}-butyric acid methyl ester (C_{71}-PCBM) perform poorly in terms of conversion efficiency. In order to enhance phase separation and improve efficiency, selected by its solubility and boiling point, 1,8-octanedithiol (ODT) is introduced as an additive in the solar cells preparation process.[7,8] Alternatively, high power conversion efficiencies can also be achieved by the introduction of a silicon bridge between the thiophene-rings, which induces the desirable phase separation between the polymer and the fullerene.[9] For example, poly[(4,40-bis(2-ethylhexyl) dithieno [3,2-b:20,30-d] silole)-2,6-diyl-alt-(2,1,3-benzothiadiazole)-4,7-diyl] (Si-PCPDTBT) was found to be a better candidate as an electron donor due to its higher crystallinity and charge mobility.[9] Without the use of additives or other post treatments, solar cells based on Si-PCPDTBT:C_{71}-PCBM blend have already reached power conversion efficiencies of over 5%.[10] It is generally accepted that a specific morphology of the bulk heterojunction is essential for achieving the optimum compromise between efficient charge carrier formation and extraction in organic solar cell devices. The morphology related photophysics and electrical properties have hence been intensively investigated.[11–13] It has been recently demonstrated that the information on domain size and local morphology of the polymer:fullerene blend films can be deduced via photoluminescence (PL) as well as Raman peak intensity and position of each component.[14–19]

In addition to efficiency, the lifetime of organic solar cells is another requirement for the success of this technology. The life-time is limited by a variety of factors, such as chemical degradation (interactions with water and oxygen)[20] including photodegradation,[21,22] as well as by physical and mechanical degradation.[23] Under ambient conditions, photodegradation of PCPDTBT:PCBM blend films has been shown to be mainly

---

Dr. X. Wang, Dr. H.-G. Mack,
Prof. A. J. Meixner, Dr. D. Zhang
Institute of Physical and Theoretical Chemistry
Auf der Morgenstelle 18
University of Tübingen
72076, Tübingen, Germany
E-mail: xiao.wang@uni-tuebingen.de;
dai.zhang@uni-tuebingen.de
Dr. H.-J. Egelhaaf
ZAE Bayern, EnCN
Fürther Str. 250
90429 Nürnberg
Dr. H. Azimi, Prof. C. J. Brabec
Institute of Materials for Electronics and Energy Technology (I-MEET)
Department of Materials Science and Engineering
Friedrich-Alexander-University
Martensstr. 7
91058 Erlangen, Germany

DOI: 10.1002/aenm.201400497

Journal of Alloys and Compounds 588 (2014) 254–258

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jalcom

Formation of Cu_2SnSe_3 from stacked elemental layers investigated by combined in situ X-ray diffraction and differential scanning calorimetry techniques

Rachmat Adhi Wibowo [a,*], Stefan Moeckel [b], Hyesun Yoo [a], Astrid Hoelzing [a], Rainer Hock [a],
Peter J. Wellmann [b]

[a] Chair for Crystallography and Structural Physics, University of Erlangen-Nürnberg, Staudtstr. 3, 91058 Erlangen, Germany
[b] Department of Materials Science, University of Erlangen-Nürnberg, Martensstr. 7, 91058 Erlangen, Germany

A R T I C L E I N F O

Article history:
Received 11 June 2013
Received in revised form 31 October 2013
Accepted 31 October 2013
Available online 9 November 2013

Keywords:
Intermetallics
Thermoelectric materials
Solid state reactions
Phase transitions

A B S T R A C T

Stacked elemental layers of Mo/Cu/Sn and Mo/Cu/Sn/Se were employed as samples for investigating the formation reaction of Cu–Sn intermetallic compounds as well as Cu_2SnSe_3 phases by in situ technique of X-ray diffraction and differential scanning calorimetry. The use of a combined in situ technique allows a real-time observation on solid-state reactions as well as any crystalline phase changes during annealing towards the crystallization of Cu_2SnSe_3. It is found that Cu and Sn form intermetallic compounds of Cu_6Sn_5, Cu_3Sn and $Cu_{41}Sn_{11}$ as the annealing temperature rises from 30 to 550 °C. The reaction of Se with Cu to form a CuSe phase dominates the binary phase formation at a low annealing temperature. The annealing of a stacked Mo/Cu/Sn/Se layer suggests that only Cu_6Sn_5 intermetallic compound directly acts as a reactant for the Cu-selenide phase formation. A SnSe phase mostly forms from a liquid-state reaction of Sn and Se above the Sn melting point. The in situ investigation also reveals a complete set of Cu-selenide peritectic decompositions of $CuSe_2 \rightarrow CuSe \rightarrow Cu_{2-x}Se$ at 380 and 412 °C. The formation of Cu_2SnSe_3 phase starts at 450 °C as a product from a reaction between $Cu_{2-x}Se$ and SnSe in a presence of liquid Se. Comparisons on the initial formation temperatures of all involved phases and on the formation pathways between Cu_2SnSe_3 and Cu_2SnS_3 are discussed as well.

1. Introduction

The research and development of the earth abundant semiconducting compound materials for photonics application have recently been attracting a great interest. The application of this sort of materials may not only reduce the photovoltaic cost but also take an advantage on the sustainable raw materials supply for large-scale and long term photovoltaic production. This emerging research field has been promoting the utilization of the earth abundant kesterite $Cu_2ZnSn(S,Se)_4$ as a promising photovoltaic materials that may replace silicon and $Cu(In,Ga)(S,Se)_2$ [1]. To improve the kesterite solar cell performance comparable to its counterparts, a fabrication of device-quality kesterite materials free of any detrimental secondary phases has been a particular challenge to overcome [2]. Some of the secondary phases are well-recognized as Cu_2SnX_3 (X = S, Se) compounds which deteriorate the kesterite solar cell performance due to their lower band gaps compared with the kesterite [3]. In conjunction with this particular challenge, studies of Cu_2SnX_3 have mostly been dedicated to support the kesterite researches, for instances the detection of a Cu_2SnX_3 secondary phase in kesterite films [4], the study of its corresponding Raman spectra for distinguishing it from kesterite spectra [5,6], the investigation of Cu_2SnS_3 formation during annealing [7] and the synthesis of Cu_2SnX_3 as a precursor for kesterite crystallization [8]. On a basis of these studies, Cu_2SnX_3 has been regarded as an essential intermediate phase in the kesterite fabrication since the kesterite formation is normally completed by the solid state reaction of Cu_2SnX_3 with ZnX. Nevertheless an in-depth experimental study of the formation of Cu_2SnSe_3 has not been reported yet.

This contribution presents the formation of Cu_2SnSe_3 films from stacked elemental layers of Mo/Cu/Sn/Se by combined in situ X-ray diffraction (XRD) and Differential Scanning Calorimetry (DSC). This study is performed not only to comprehend the formation reactions during the selenization of metallic precursors towards the optimization of kesterite absorber and photovoltaic device fabrication, but also to give a chemical reaction insights on the synthesis of a Cu_2SnSe_3 compound for other completely different applications. Although Cu_2SnX_3 compounds as secondary phases in the kesterite deteriorates cell performance, it has been explored that their low band gap characteristic offers a technological advantage

---

[*] Corresponding author. Present address: Austrian Institute of Technology, Giefinggasse 2, 1210 Vienna, Austria. Tel.: +43 505506630; fax: +43 505506111.
E-mail address: wibowo@krist.uni-erlangen.de (R.A. Wibowo).

0925-8388/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jallcom.2013.10.245

Thin Solid Films 564 (2014) 213–217

Contents lists available at ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

Stabilization of aluminum doped zinc oxide nanoparticle suspensions and their application in organic solar cells

N. Wolf [a,*], T. Stubhan [b], J. Manara [a], V. Dyakonov [a], C.J. Brabec [b,c]

[a] Bavarian Center for Applied Energy Research (ZAE Bayern), Division: Energy Efficiency, Am Galgenberg 87, 97074 Würzburg, Germany
[b] Institute of Materials for Electronics and Energy Technology (i-MEET), Friedrich-Alexander University of Erlangen-Nuremberg, Martensstraße 7, 91058 Erlangen, Germany
[c] Bavarian Center for Applied Energy Research (ZAE Bayern), Division: Renewable Energies, Haberstraße 2a, 91058 Erlangen, Germany

ARTICLE INFO

Article history:
Received 24 October 2013
Received in revised form 8 May 2014
Accepted 4 June 2014
Available online 11 June 2014

Keywords:
Aluminum doped zinc oxide
Nanoparticle suspensions
Interfacial layers
Inverted polymer–fullerene solar cells

ABSTRACT

Aluminum doped zinc oxide (AZO) nanoparticles were redispersed in isopropyl alcohol and stabilized with different stabilizers and mixtures of stabilizers that allow for electronically functional particles. The size of the redispersed nanoparticles was small enough to use these suspensions to build interfacial layers in inverted polymer–fullerene solar cells. The performance of these devices was found to depend on the stabilizer used in the nanoparticle suspension. The best performance was obtained with an AZO interfacial layer built with a 3,6,9-trioxadecanoic acid and polyvinylpyrrolidone stabilized nanoparticle suspension.

1. Introduction

Transparent conductive oxide (TCO) coatings have a variety of applications and are used for example as electrodes in flat-panel displays (liquid crystal displays, organic light-emitting diodes, plasma display panel) [1], touch screens [2], transparent thin film transistors [3], coatings for energy-efficient windows [4] or organic solar cells [5]. The most common and frequently used TCOs are tin doped indium oxide (ITO), aluminum or gallium doped zinc oxide (AZO or GZO) and fluorine or antimony doped tin oxide (FTO or ATO) [6]. Thin TCO layers can be fabricated by using a lot of different techniques like chemical and physical vapor deposition such as spray pyrolysis [7], electron beam evaporation [8], DC sputtering [9] or radio frequency magnetron sputtering [10]. The disadvantages of these techniques are that they are rather expensive due to vacuum processing [8,11] and they are often only applicable to planar substrates. Low-cost and economical alternative deposition techniques are wet chemical depositions like conventional sol–gel routines [12] or redispersed nanoparticle suspensions [13–16].

Coatings which have been fabricated with TCO nanoparticle suspensions show higher specific electrical resistivities and higher porosities than coatings which have been prepared with conventional sol–gel routines. But the huge advantage of nanoparticle suspensions is that the layer deposition does not require high temperatures because the metal oxide formation is uncoupled from the formation of the functional layer [16]. The curing of the layers can take place at temperatures which are far below 150 °C. Therefore it is possible to produce layers on polymers like polycarbonate or to use these layers as interfacial layers in organic bulk-heterojunction solar cells which are especially built in the standard architecture. In the standard cell structure the TCO interfacial layer processed via a nanoparticle suspension is deposited on top of the semiconductor and beneath the top cathode that means high temperature annealing processes will harm the polymeric active layer. Besides the high temperatures the used nanoparticle suspension must not contain any chemicals like e.g. ethylene glycol which will also harm the cell.

The most widespread solution processed TCOs for n-type contacts in organic photovoltaic (OPV) are titanium oxide (TiOx) [17–20] and zinc oxide (ZnO) [20–24]. Some results with doped metal oxides were reported as well [5,20,25,26]. The enhanced conductivity and charge carrier density of these materials were shown to allow thicker interface layers [5] and could improve contact formation to the metal [25]. This demonstrates a pathway to reliable large scale printing on the one hand and to the use of stable high work function metals as cathodes in OPV on the other hand.

Therefore stable aluminum doped zinc oxide (AZO) nanoparticle suspensions have been developed and fabricated in this work in order to use them as interfacial layers in organic solar cells.

Stable nanoparticle suspension with tin doped indium oxide (ITO) nanoparticles has been prepared and investigated for several years [27,28] and there are a lot different formulas to produce stable ITO nanoparticle suspensions [15,16,29–34]. Also formulas for stable ZnO nanoparticle suspensions have been reported [35–38], but only one publication describes stable AZO nanoparticle suspensions so far [3]. In

---

[*] Corresponding author. Tel.: +49 931 70564 221; fax: +49 931 70564 600.
E-mail address: nadine.wolf@zae-bayern.de (N. Wolf).

http://dx.doi.org/10.1016/j.tsf.2014.06.009

CM CHEMISTRY OF MATERIALS

Communication

pubs.acs.org/cm

Improved High-Efficiency Perovskite Planar Heterojunction Solar Cells via Incorporation of a Polyelectrolyte Interlayer

Hong Zhang,*,†,§ Hamed Azimi,† Yi Hou,†,§ Tayebeh Ameri,† Thomas Przybilla,‡ Erdmann Spiecker,‡
Mario Kraft,⊥ Ullrich Scherf,⊥ and Christoph J. Brabec†,∥

†Institute of Materials for Electronics and Energy Technology (i-MEET), Friedrich-Alexander-University Erlangen-Nuremberg, Martensstraße 7, 91058 Erlangen, Germany

∥Bavarian Center for Applied Energy Research (ZAE Bayern), Haberstraße 2a, 91058 Erlangen, Germany

§Erlangen Graduate School in Advanced Optical Technologies (SAOT), Paul-Gordan-Straße 6, 91052 Erlangen, Germany

⊥Macromolecular Chemistry Group (buwmakro) and Institute for Polymer Technology (IfP), Bergische Universität Wuppertal, Gaußstraße 20, 42119 Wuppertal, Germany

‡Center for Nanoanalysis and Electron Microscopy (CENEM), University of Erlangen-Nuremberg, Cauerstrasse 6, 91058 Erlangen, Germany

Supporting Information

Photovoltaic devices that have light weights, are mechanically flexible, have good solution-processability, are low cost, and have high efficiency have been studied intensively in the past decade.[1−3] In 2009, Miyasaka et al.[4] reported a first attempt using perovskites as sensitizers incorporated into dye-sensitized solar cells, which represents a revolutionary step in perovskite photovoltaic technology. Organolead halide perovskite materials, ABX_3 ($A = CH_3NH_3$ or NH_2CHNH_2, $B = Pb$, and $X = Br$, Cl, or I) are the subject of extensive investigations. This kind of perovskite material offers a broad range of attractive features such as a direct optical bandgap, a low exciton binding energy and long diffusion length, a broad range of light absorption, and excellent carrier transport and crystallinity.[4,5,7−13] Recently, significant progress has been realized in organolead halide perovskite photovoltaic devices with efficiencies over 15%,[10,14−18] attracting tremendous attention in the photovoltaic industry. Yang et al. reported a record-breaking efficiency of 19.3% in lead-based perovskite solar cells.[19] However, the fabrication of most efficient perovskite solar cells is typically performed based on employing a high-quality condensed TiO_2 layer as electron transporting layer, which requires high-temperature processing (450 °C) for a long time (1 h).[17,18] Efficient perovskite solar cells can be also fabricated using a hybrid planar heterojunction (PHJ), in which the perovskite layer is sandwiched between a hole-transport layer, poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate) (PEDOT:PSS), and an electron-transport layer, [6,6]-phenyl-C61-butyric acid methyl (PCBM). The advantages of this structure are the simplicity as well as low-temperature solution-processability.[3,19,20−22] However, the barrier at the contact interface between a Fermi level of various electrode metals (e.g., Ag, Au) and the lowest unoccupied molecular orbital (LUMO) of the organic material (PCBM) still exists in organic optoelectronic devices, leading to poor electron injection and extraction.[23,24] The charge injection and extraction at the metal−organic semiconductor interface has a significant impact on the electrical properties of the semiconductor devices. To minimize the contact barrier, the interface between the metal electrode and the PCBM layer should be a quasi-ohmic contact. The suitability of the interface opens the opportunity to apply the interface design rules for the organic solar cell to the perovskite solar cell technology. That strategy has led to efforts in interfacial engineering of hybrid organic/inorganic perovskite PHJ solar cells. High fill factors were demonstrated with, e.g., the use of thermal vapor deposited LiF,[25] bathocuproine (BCP),[20,21] or fullerene (C_{60})[26] on top of the PCBM layer. All these systems improved the contact properties and enhanced the device efficiency. However, the thermal vapor deposition of an interface layer is the contradiction to the concept of large scale fabrication and cost-effective solution processing.

In this work, we demonstrate that high efficient hybrid organic/inorganic perovskite PHJ solar cell can be fabricated by inserting an ultrathin polyelectrolyte layer, either ethoxylated polyethylenimine (PEIE) or poly[3-(6-trimethylammoniumhexyl)thiophene] (P3TMAHT). Both layers are processed from methanol on top of PCBM and beneath the Ag electrode. The power conversion efficiency (PCE) increases from 8.53% to 12.01% (PEIE) and 11.28% (P3TMAHT) for the solution-processed polyelectrolyte-modified interfaces. The creation of a surface dipole between PCBM and Ag electrode opens up an alternative pathway to engineer the interface of hybrid organic/inorganic perovskite PHJ solar cells. It is noteworthy to mention that the identical strategy was successfully demonstrated for organic solar cells.[27,28]

Figure 1a shows the molecular structures of the interlayer materials, PEIE and P3TMAHT, and the device configuration of the hybrid organic/inorganic perovskite PHJ solar cell. The polyelectrolyte interlayers were subsequently deposited by spin-casting from PEIE (0.2% w/v) and P3TMAHT (0.01% w/v) solutions in methanol. A cross-sectional scanning electron microscopy (SEM) image of the device without the Ag electrode is shown in Figure 1b. The cross-section was prepared

Received: August 4, 2014
Revised: August 27, 2014
Published: August 27, 2014

Journal of
Materials Chemistry A

PAPER

View Article Online
View Journal | View Issue

Cite this: J. Mater. Chem. A, 2014, 2, 18917

A solution-processed barium hydroxide modified aluminum doped zinc oxide layer for highly efficient inverted organic solar cells†

Hong Zhang,[*abc] Tobias Stubhan,[a] Ning Li,[a] Mathieu Turbiez,[d] Gebhard J. Matt,[a]
Tayebeh Ameri[a] and Christoph J. Brabec[ab]

Received 4th July 2014
Accepted 8th September 2014

DOI: 10.1039/c4ta03921j

www.rsc.org/MaterialsA

Inverted organic solar cells (IOSCs) with air stable interface materials and top electrodes and an efficiency of 6.01% are achieved by inserting a barium hydroxide (Ba(OH)$_2$) layer between the aluminum doped zinc oxide (AZO) electron extraction layer and the active layer. A low bandgap diketopyrrolopyrrole-quinquethiophene alternating copolymer (pDPP5T-2) and phenyl-C61-butyric acid methyl ester (PC$_{61}$BM) were chosen as the active layer compounds. Compared to the control device without Ba(OH)$_2$, insertion of a few nm thick Ba(OH)$_2$ layer results in an enhanced V_{OC} of 10%, J_{SC} of 28%, FF of 28% and PCE of 80%. Modification of AZO with a solution processed low-cost Ba(OH)$_2$ layer increased the efficiency of the inverted device by dominantly reducing the energy barrier for electron extraction from PC$_{61}$BM, and consequently, reduced charge recombination is observed. The drastic improvement in device efficiency and the simplicity of fabrication by solution processing suggest Ba(OH)$_2$ as a promising and practical route to reduce interface induced recombination losses at the cathode of organic solar cells.

1. Introduction

Organic solar cells (OSCs) were studied intensively in the last decade due to their remarkable properties such as mechanical flexibility, low-cost, light weight and low energy consuming roll-to-roll manufacturing process.[1-4] Recently, OSCs showed impressive power conversion efficiency (PCE) with over 10% for a laboratory test cell.[5] Developing the OSC technology towards industrial commercialization is thus the focus of extensive research. The physical and chemical properties of the semiconductor/electrode interface were found to be the most critical factors in determining the device characteristics and stability.[6]

Inverted organic solar cells (IOSCs) rapidly evolved with the progress of n-type inorganic metal oxides (MeO$_x$) as electron transport layers, such as titanium oxide (TiO$_x$), zinc oxide (ZnO) or aluminum doped zinc oxide (AZO).[7-10] Metal oxides have emerged because of their intrinsically higher environmental stability as compared to poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) or calcium (Ca) charge transport layers.[11] However, solution processed metal oxides are far away from the properties of single crystals, and defect related energy levels or Schottky barriers may form interfacial barriers.[12-14] Lee *et al.* and others reported poor electron injection and extraction in/from organic optoelectronic devices with metal oxide interfacial layers due to a contact barrier between the n-type metal oxides and the lowest unoccupied molecular orbital (LUMO) of the acceptor of the active layer.[6,15-17] Schematics of various types of energy level mismatch between the n-type metal oxides (MeO$_x$) and the acceptor of the active layer (PCBM) and their implication on the J–V characteristics are shown in Fig. 1.[12,18,19] (a) An injection barrier is formed when the work function of the MeO$_x$ is below the Fermi level, the LUMO level of PCBM, respectively. Such an injection barrier prevents electron injection at the MeO$_x$/PCBM interface. An injection barrier primarily implies an increased series resistance, and, if contact formation follows the integer charge transfer (ICT) model,[20] a potentially lower built-in potential V_{bi} (as compared to the HOMO$_{donor}$ − LUMO$_{acceptor}$ difference). A delayed injection results in a higher series resistance or even an s-shaped J–V curve in the 1st quadrant in combination with a potentially lower V_{OC}. (b) An extraction barrier implies that charges cannot be extracted from the active layer to the metal oxide because the conduction band of MeO$_x$ is high above the LUMO of PCBM. Such an extraction barrier becomes visible as a strong bias dependence of the photocurrent under reverse bias, *i.e.* in the 3rd/4th quadrant. (c) The combination of extraction and injection barriers results in an s-shaped J–V curve (1st quadrant) in

---

[a] Institute of Materials for Electronics and Energy Technology (I-MEET), Friedrich-Alexander-University Erlangen-Nürnberg, Martensstraße 7, 91058 Erlangen, Germany. E-mail: Hong.Zhang@fau.de; Fax: +49 (0)9131 8528495; Tel: +49 (0)9131 8527732

[b] Bavarian Center for Applied Energy Research (ZAE Bayern), Haberstraße 2a, 91058 Erlangen, Germany

[c] Erlangen Graduate School in Advanced Optical Technologies (SAOT), Paul-Gordan-Straße 6, 91052 Erlangen, Germany

[d] BASF Schweiz AG, Schwarzwaldallee 215, CH-4058 Basel, Switzerland

† Electronic supplementary information (ESI) available. See DOI: 10.1039/c4ta03921j

Journal of Luminescence 154 (2014) 198–203

Contents lists available at ScienceDirect

Journal of Luminescence

journal homepage: www.elsevier.com/locate/jlumin

Luminescent properties and energy transfer processes in YAG:Er single crystalline films

Yu. Zorenko[a,*], V. Gorbenko[a,b], T. Zorenko[a,b], V. Savchyn[b], M. Batentschuk[c], A. Osvet[c], C. Brabec[c]

[a] Institute of Physics, Kazimierz Wielki University in Bydgoszcz, Powstańców Wielkopolskich 2, 85-090 Bydgoszcz, Poland
[b] Laboratory of Optoelectronic Materials (LOM), Ivan Franko National University of Lviv, Gen. Tarnavskiy Str. 107, 79017 Lviv, Ukraine
[c] Department of Materials Science 6, University of Erlangen-Nürnberg, Martensstrasse 7, D-91058 Erlangen, Germany

ARTICLE INFO

Article history:
Received 1 November 2013
Received in revised form
10 April 2014
Accepted 22 April 2014
Available online 30 April 2014

Keywords:
Single crystalline films
Liquid phase epitaxy
Luminescence
YAG
Er^{3+} dopant

ABSTRACT

The paper is dedicated to studying the optical properties of YAG:Er single crystalline films (SCF) grown by liquid phase epitaxy. The absorption, cathodoluminescence and photoluminescence spectra were measured for the YAG:Er SCFs with different doping levels of Er^{3+} from 0.735 to 6.6 at%. The luminescence spectra and luminescence excitation spectra under synchrotron radiation excitation in the fundamental absorption range of the YAG and in the intrinsic f–d absorption bands of Er^{3+} ions reveal the peculiarities of energy transfer from the YAG host to the Er^{3+} ions.

1. Introduction

$Y_3Al_5O_{12}$ (YAG) garnet doped with rare earth ions is a well-known optical material for different optoelectronic applications. Single crystals (SC) and single-crystalline films (SCF) of YAG, doped with Ce^{3+} and Pr^{3+} ions, are used as scintillators for the visualization of X-ray images [1,2] and as cathodoluminescent screens [3]. Nowadays, the YAG:Er SC are also considered for scintillation applications [4].

Under excitation in the range of band-to-band transitions of YAG host, intense complex intrinsic luminescence in the UV range arises in the melt-grown undoped and rare-earth (R^{3+}) doped YAG SC [5–8]. This emission is related to the luminescence of excitons "localized near" and "bound with" the Y_{Al} antisite defects (AD) [5,6]. Emission of the AD-related centers can partly overlap with the R^{3+} ion absorption bands, which influence the decay characteristics of YAG:R^{3+} SC scintillators [7,8]. The Y_{Al} ADs in YAG SC can also play the role of shallow electron traps, which are responsible for intensive thermoluminescence peaks between 100 and 200 K [9–11] and can be one of the reasons for the considerable amount of very slow decay components in the scintillation response of Ce^{3+} and Pr^{3+} doped YAG and $Lu_3Al_5O_{12}$ (LuAG) bulk SC scintillators [7,8].

It is important to note that in the melt-grown YAG SC another type of AD centers is also found – R^{3+} ions at the sites of Al^{3+} cations (R_{Al} centers) [12–16]. Absorption and luminescence of R_{Al} centers were observed for the first time in SCs of Er doped YAG, $Y_3Ga_5O_{12}$ (YGG) and $Gd_3Ga_5O_{12}$ (GGG) garnets [12,13]. The creation of Er_{Al} centers is very probable in the condition of high-temperature crystallization of SC of the mentioned garnets from the melt. Other type of the R_{Al} centers, namely Ce_{Al} centers, was found in Ce^{3+} doped YAG and LuAG SCs using the optical absorption [14], luminescence [15] and electron paramagnetic resonance [16].

In our previous works [2,5–8,14–16] we have found that the formation of Y_{Al} and R_{Al} ADs is completely suppressed in SCF of garnets grown by the liquid phase epitaxy (LPE) method at relatively low (~1000 °C) temperatures. As a result of AD elimination, the YAG:Ce and LuAG:Ce SCFs possess better time response under excitation in the range of interband transitions with respect to their bulk SC analogs [6,17]. In addition, the AD-free undoped and rare-earth doped YAG SCF provide useful samples for the investigation of the fundamental optical properties of the YAG host and its rare-earth dopants, allowing the study of absorption [14], intrinsic and impurity related luminescence [2,5–8] without any contribution of the AD related centers. At the same time, to our knowledge, no direct confirmation of the absence of Er_{Al} centers in Er doped YAG SCF has been performed up to now.

Er^{3+}, Yb^{3+} and Nd^{3+} doped YAG SC, SCF and ceramics are also well-known laser media with laser action in the near and deep infra-red range [18–20]. Specifically, Er^{3+} doped YAG shows laser emission around 1500 nm due to the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transitions of Er^{3+} ions [18,19]. In the Er^{3+} doped YAG the infrared-visible up-conversion

---

[*] Corresponding author. Tel.: +48691130836.
E-mail address: zorenko@ukw.edu.pl (Yu. Zorenko).

http://dx.doi.org/10.1016/j.jlumin.2014.04.029
0022-2313/

Conference Proceedings

Frank W. Fecher, Jens Adams, Andreas Vetter, Claudia Buerhop-Lutz, Christoph J. Brabec
Loss analysis on CIGS-modules by using contactless, imaging illuminated lock-in thermography and 2D electrical simulations
IEEE 40th Photovoltaic Specialist Conference, PVSC 2014, art. no. 6925648, pp. 3331-3334, 2014

V. Grivickas, K. Gulbinas, V. Jokubavičius, J. W Sun, M. Karaliūnas, S. Kamiyama, M. Linnarsson, M. Kaiser, P. Wellmann and M. Syväjärvi
Carrier Lifetimes and Influence of In-Grown Defects in N-B Co-Doped 6H-SiC
EMRS 2013 Spring Meeting, Symposium G, IOP Conf. Series: Materials Science and Engineering ***56,*** *012004, 6 pages, 2014*

Fei Guo, Peter Kubis, Thomas Przybilla, Erdmann Spiecker, Karen Forberich, Christoph J. Brabec
Semitransparent organic photovoltaic modules with Ag nanowire top Electrodes
Proceedings of SPIE - Organic Photovoltaics XV, Vol. ***9184D****, 2014*

M. Kaiser, S. Schimmel, V. Jokubavicius, M. K. Linnarsson, H. Ou, M. Syväjärvi and P. Wellmann
Nucleation and growth of polycrystalline SiC
EMRS 2013 Spring Meeting, Symposium G, IOP Conf. Series: Materials Science and Engineering ***56,*** *012001, 6 pages, 2014*

Peter Kubiš, Fei Guo, George Spyropolous, Monika M. Voigt, Christoph J. Brabec
Patterning of OPV modules by ultra-fast laser
Proceedings of SPIE - Laser Processing and Fabrication for Solar, Displays, and Optoelectronic Devices III, Vol. ***9180****, 2014*

Georg Neubauer, Michael Salamon, Norman Uhlmann, Peter J. Wellmann
Real-time Measurement of the Evolution of Growth Facets during SiC PVT Bulk Growth using 3-D X-ray Computed Tomography
Materials Science Forum Vols. ***778-780****, pp 9-12, 2014*

S. Schimmel, M. Kaiser, V. Jokubavicius2, Y. Ou, P. Hens, M. K. Linnarsson, J. Sun, R. Liljedahl, H. Ou, M. Syväjärvi, P. Wellmann
The role of defects in fluorescent silicon carbide layers grown by sublimation epitaxy
EMRS 2013 Spring Meeting, Symposium G, IOP Conf. Series: Materials Science and Engineering ***56,*** *012002, 6 pages, 2014*

Anastasiia Solodovnyk, Andre Hollmann, Andres Osvet, Karen Forberich, Edda Stern, Miroslaw Batentschuk, Robin Klupp Taylor, and Christoph J. Brabec
Luminescent Down-Shifting Layers with Eu^{2+} and Eu^{3+} Doped Strontium Compound Particles for Photovoltaics
Proceedings of SPIE - Next Generation Technologies for Solar Energy Conversion V, Vol. ***9178*** *917806-1, 11 pages, 2014*

Anastasiia Solodovnyk, Benjamin Lipovšek, Karen Forberich, Edda Stern, Miroslaw Batentschuk, Marko Topič, and Christoph J. Brabec
Light Propagation in Phosphor-Filled Matrices for Photovoltaic PL Down-Shifting
Proceedings of SPIE - Reflection, Scattering, and Diffraction from Surfaces IV, Vol. ***9205****, 92050D, 9 pages, 2014*

Peter Wellmann, Mikael Syväjärvi and Haiyan Ou
Alternative approaches of SiC & related wide bandgap materials in light emitting & solar cell applications
EMRS 2013 Spring Meeting, Symposium G, IOP Conf. Series: Materials Science and Engineering ***56,*** *011001, 2 pages, 2014*

2014 IEEE 40th Photovoltaic Specialist Conference, PVSC 2014
15 October 2014, Article number 6925648, Pages 3331-3334

Loss analysis on CIGS-modules by using contactless, imaging illuminated lock-in thermography and 2D electrical simulations

Frank W. Fecher[1,2], Jens Adams[1], Andreas Vetter[2], Claudia Buerhop-Lutz[1], Christoph J. Brabec[1,2]

[1] Bayerisches Zentrum für Angewandte Energieforschung e.V. (ZAE Bayern), 91058 Erlangen, Germany;
[2] Lehrstuhl für Materialien der Elektronik und Energietechnologie (i-MEET), Friedrich-Alexander-Universität Erlangen-Nürnberg, 91058 Erlangen, Germany

Abstract **— Loss analysis on CIGS-modules are demonstrated by using contactless, imaging illuminated lock-in thermography (ILIT). Power dissipating defects, like shunts, were visualized in commercially manufactured test modules (30 x 30 cm²). The evaluations of the ILIT-measurements displayed a correlation with the loss in maximum output power and in open circuit voltage; 2D finite element simulations of the shunts confirmed the correlations. A further simulative parameter study gives a deep understanding of the influence of a shunt on the electrical performance in thin film modules.**

As ILIT is a contactless and fast method, it has the potential to become a powerful tool for in-line characterization. Furthermore, we consider this technique to be applicable also to other thin film module technologies, like CdTe, a-Si:H or organic photovoltaics.

Index Terms **— lock-in thermography, module performance, photovoltaic, Pmpp, shunt, Voc.**

I. INTRODUCTION

Illuminated lock-in thermography (ILIT) is a versatile tool for detecting shunts and imaging of dissipative power losses in solar cells [1]–[3]. Its charm is based on the possibility of contactless measurements under open circuit conditions. By this, ILIT would be an ideal candidate for in-line control during the production process.

The application of ILIT measurements states a new challenge, especially for predicting module performances, as promising photovoltaic technologies like CuInGaSe2 (CIGS) [4] are produced as large area monolithic series connected modules.

Here, we demonstrate contactless and quantitative determinations of the open circuit voltage (V_{oc}) and the maximum power output (P_{mpp}) of non-encapsulated CIGS test modules using ILIT under open circuit conditions [5], [6]. This is done by analysis of the power losses (e.g. shunts) and finding correlations between ILIT-signal and cell / module performance.

Recent publications presented electrical 2D simulations of thin film modules including shunts [7]–[9]. Such simulations were performed to give a deeper understanding into the influence of a shunt on the module performance and the dependence on the shunt position [9].

II. RESULTS AND ANALYSIS/DISCUSSION

In the following we describe the results from our ILIT-investigations of non-encapsulated CIGS test modules (30 x 30 cm²) under open circuit conditions. The evaluation of the ILIT-images (including post-processing) showed a correlation with the V_{oc} of the cells [5] and with the P_{mpp} of the modules [6]. All measurements were performed under low light conditions (P_{ill} = 30 W/m²). Furthermore, a simulative study exhibits that the position of a shunt inside the cell influences the module performance [9]. This result will be analyzed and be explained in detail.

A. Determining the loss in V_{oc}

The performance parameter V_{oc} of a cell is influenced by leakage currents that can arise from macroscopic defects like shunts. Fig. 1 shows an ILIT-image of such a shunt in the third cell. The shunt's ILIT-signal is much higher than the rest of the module and the shunted cell shows a lower signal than the other cells.

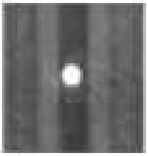


Fig. 1. Section of amplitude image of ILIT-measurement of CIGS-module with shunt in third cell. (P_{ill} = 30 W/m², Frequency = 1 Hz, Time = 33 min., open circuit conditions)

In the experiments, 220 cells (distributed in 15 CIGS test modules) containing one or more shunts were investigated. Therefore, the ILIT-signals of the shunts were evaluated and the V_{oc} of the shunted cells were measured. The V_{oc} of the shunted cell was related to the V_{oc} of a non-shunted cell and plotted versus the ILIT-signal in Fig. 2. This plot shows a good correlation between the V_{oc} and the ILIT-signal. The relative cell V_{oc} decreases almost linear from 1.0 down to 0.8

978-1-4799-4398-2/14/$31.00 ©2014 IEEE

Carrier Lifetimes and Influence of In-Grown Defects in N-B Co-Doped 6H-SiC

V Grivickas[1], K Gulbinas[1], V Jokubavičius[2], J W Sun[2], M Karaliūnas[1], S Kamiyama[3], M Linnarsson[4], M Kaiser[5], P Wellmann[5] and M Syväjärvi[2]
[1]Institute of Applied Research, Vilnius University, Saulėtekio av. 10, Vilnius, 10223 Lithuania
[2]Department of Physics, Chemistry and Biology, Linköping University, Linköping, 58183 Sweden
[3]Faculty of Science and Technology, Meijo University, Tempaku-ku, Nagoya, 468-8502 Japan
[4]School of Information and Communication Technology, Royal Institute of Technology, Kista-Stockholm, 58183 Sweden
[5]Department of Materials Science – Materials for Electronics and Energy Technology, University of Erlangen-Nuremberg, Erlangen, 91058 Germany

E-mail: vytautas.grivickas@ff.vu.lt

Abstract. The thick N-B co-doped epilayers were grown by the fast sublimation growth method and the depth-resolved carrier lifetimes have been investigated by means of the free-carrier absorption (FCA) decay under perpendicular probe-pump measurement geometry. In some samples, we optically reveal in-grown carbon inclusions and polycrystalline defects of substantial concentration and show that these defects slow down excess carrier lifetime and prevent donor-acceptor pair photoluminescence (DAP PL). A pronounced electron lifetime reduction when injection level approaches the doping level was observed. It is caused by diffusion driven non-radiative recombination. However, the influence of surface recombination is small and insignificant at 300 K.

1. Introduction

B and N co-doped 6H-SiC epilayers combined with GaN-ultraviolet excitation chip can be used as an active material in a high-efficiency LED structure stack for a visible broad spectral light generation by DAP emission mechanism [1,2]. As accounted theoretically, this concept from blue excitation light could provide internal energy conversion up to 70% with a high color quality of a white spectrum. Moreover, in SiC it is possible to obtain uniform concentration of impurities in depth of hundred microns. It is well known that SiC material itself has excellent thermal conductivity property which is important for high power LED performance. Therefore, high co-doping in SiC requires further understanding of the growth techniques and investigation of optical properties. Up to now, very little is known on impurity clustering, on actual carrier transport mechanism and on the competing nonradiative recombination channels [3, 4]. In addition, an impact of co-doped acceptor situated on the hexagonal and the cubic sites in 6H-SiC matrix and their influence in the DAP processes is also not completely established yet [5].

In this work we present the free-carrier-absorption (FCA) lifetime studies performed on thick N-B doped epilayers in order to elucidate influence of surface and bulk recombination. We focus on previously observed pronounced injection dependence of the carrier lifetimes [3]. The surface recombination is estimated by performing the depth-resolved FCA measurement. Furthermore, we

Nucleation and growth of polycrystalline SiC

M Kaiser[1], S Schimmel[1], V Jokubavicius[2], M K Linnarsson[3], H Ou[4], M Syväjärvi[2] and P Wellmann[1]

[1]Materials Department 6, University of Erlangen, Martensstrasse 7, D-91058 Erlangen, Germany
[2]Department of Physics, Chemistry and Biology, Linköping University, SE-58183 Linköping, Sweden
[3]School of Information and Communication Technology, KTH Royal Institute of Technology, SE-16440 Kista, Sweden
[4]Department of Photonics Engineering, Technical University of Denmark, DK-2800 Lyngby, Denmark

E-mail: michl.kaiser@ww.uni-erlangen.de

Abstract. The nucleation and bulk growth of polycrystalline SiC in a 2 inch PVT setup using isostatic and pyrolytic graphite as substrates was studied. Textural nucleation occurs under near-thermal equilibrium conditions at the initial growth stage with hexagonal platelet shaped crystallites of 4H, 6H and 15R polytypes. It is found that pyrolytic graphite results in enhanced texturing of the nucleating gas species. Reducing the pressure leads to growth of the crystallites until a closed polycrystalline SiC layer containing voids with a rough surface is developed. Bulk growth was conducted at 35 mbar Ar pressure at 2250°C in diffusion limited mass transport regime generating a convex shaped growth form of the solid-gas interface leading to lateral expansion of virtually [001] oriented crystallites. Growth at 2350°C led to the stabilization of 6H polytypic grains. The micropipe density in the bulk strongly depends on the substrate used.

1. Introduction

Fluorescent silicon carbide (f-SiC) is a promising candidate in the field of optoelectronics for the fabrication of a novel monolithic all-semiconductor white LED structure [1]. Such devices require thick layers (> 100μm) of high crystalline quality and proper doping. The *fast sublimation growth process* (FSGP), a sublimation epitaxial technique, is proven to fulfil these requirements for growing f-SiC [2] when adequately doped solid state source materials are applied. In the case of fluorescent SiC, the research is very new and donor-acceptor co-doped sources are necessary. As no such materials exist we have previously reported on polycrystalline nitrogen and boron doped bulk SiC crystals grown using the *physical vapour transport* (PVT) technique [3]. It was also stated elsewhere that such source material is beneficial regarding minimization of graphitisation in the source and achievable layer quality at high growth rates [4].

In this work we investigate the growth of SiC crystallites on isostatically pressed highly purified and hereon deposited pyrolytic graphite substrates at the initial stages of growth of polycrystalline bulk SiC source material, i.e. when diffusion limited mass transport is activated due to the decrease of the environmental argon system pressure. The shape of the crystals, their orientation and density distribution in radial direction of the substrate is treated using optical and electron microscopy (SEM) as well as x-ray powder diffraction (XRD) as analytical methods. The results are in agreement with the temperature field distribution inside the growth chamber derived from numerical calculations using the Virtual Reactor® code. Moreover, results from polycrystalline bulk growth experiments on the before mentioned substrates at higher temperature are presented and the influence on polytype stabilization and structural quality is discussed. Additionally, the modification of texture during bulk growth is explained in terms of growth kinetics.

Materials Science Forum Vols. 778-780 (2014) pp 9-12
Online available since 2014/Feb/26 at www.scientific.net
© (2014) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/MSF.778-780.9

Real-time Measurement of the Evolution of Growth Facets during SiC PVT Bulk Growth using 3-D X-ray Computed Tomography

Georg Neubauer[1, a*], Michael Salamon[2, b], Norman Uhlmann[2],
Peter J. Wellmann[1, c]

[1]Materials for Electronics and Energy Technology, Friedrich-Alexander-Universität Erlangen-Nürnberg, Martensstr. 7, 91058 Erlangen, Germany

[2]Fraunhofer Institute for Integrated Circuits, Development Center for X-Ray Technology (EZRT), Flugplatzstr. 75, 90768 Fürth, Germany

[a]crystalgrowth.neubauer@fau.de, [b]michael.salamon@iis.fraunhofer.de,
[c]peter.wellmann@ww.uni-erlangen.de

Keywords: 3-D X-ray Computed Tomography, CT, Silicon Carbide, SiC, Bulk Crystal Growth, PVT, Sublimation Growth, Reconstructed 3-D Volume Data, In-situ Observation, Facet

Abstract: In this paper, we present our technique for obtaining a real-time 3-D volume shape of the SiC crystal using X-ray computed tomography (CT). In particular, it is possible to determine in-situ the shape of the growth interface with high precision at growth temperatures above 2000 °C in a conventional 3" physical vapor transport (PVT) growth system. We show that the size and shape of a facet can be monitored at different stages during growth and furthermore the crystal's face boundary can be determined with high precision throughout the whole growth process. Real-time in our case means recording one image sequence within 2 to 15 minutes depending on the quantity and quality of the images.

Introduction

Silicon carbide (SiC) wafer substrates, suitable for fabricating high performance power electronic devices, are by now commercially available from several companies in the industry with a rather good crystalline quality, low defect densities and diameters up to 6''. However, improvements of the growth process itself and obtaining more fundamental data about different growth related mechanisms are still an ongoing issue. In contrast to growing crystals from the melt by the Czochralski process where it is possible to observe the crystal optically during growth, the PVT sublimation growth technique for producing SiC crystals doesn't allow any optical inspection of the growth chamber's interior. The application of X-ray technology at our department for in-situ visualization of the SiC crystal in the PVT reactor has lead in recent years to several important results on mass transport, polytype switching and defect generation. There are several publications about gaining 2-D X-ray radiography and X-ray diffraction images from the crystal during growth [1-5], which improved the basic understanding of silicon carbide crystal growth. Based on past research, our goal is to significantly improve the image quality by using 3-D X-ray computed tomography.

Experimental

For this study, a standard growth reactor was used with the specific design feature of three additional mechanical alignment degrees of freedom of the growth chamber to enable advanced X-ray experiments. This PVT system had already been used for X-ray diffraction experiments in the past before the CT system was adapted to the setup [4,5]. A suitable X-ray source and a digital flat panel X-ray detector were attached to the frame of the PVT setup in order to record the required

The role of defects in fluorescent silicon carbide layers grown by sublimation epitaxy

S Schimmel[1], M Kaiser[1], V Jokubavicius[2], Y Ou[3], P Hens[2], M K Linnarsson[4], J Sun[2], R Liljedahl[2], H Ou[3], M Syväjärvi[2], P Wellmann[1]

[1] Materials Department 6, University of Erlangen, Martensstrasse 7, D-91058 Erlangen, Germany
[2] Department of Physics, Chemistry and Biology, Linköping University, SE-58183 Linköping, Sweden
[3] Department of Photonics Engineering, Technical University of Denmark, DK-2800 Lyngby, Denmark
[4] School of Information and Communication Technology, KTH Royal Institute of Technology, SE-16440 Kista, Sweden

E-mail: saskia.schimmel@ww.uni-erlangen.de

Abstract. Donor-acceptor co-doped SiC is a promising light converter for novel monolithic all-semiconductor white LEDs due to its broad-band donor-acceptor pair luminescence and potentially high internal quantum efficiency. Besides sufficiently high doping concentrations in an appropriate ratio yielding short radiative lifetimes, long nonradiative lifetimes are crucial for efficient light conversion. The impact of different types of defects is studied by characterizing fluorescent silicon carbide layers with regard to photoluminescence intensity, homogeneity and efficiency taking into account dislocation density and distribution. Different doping concentrations and variations in gas phase composition and pressure are investigated.

1. Introduction

Donor-acceptor co-doped SiC was first recognized as a potential light converter for a novel monolithic all-semiconductor white LED by Kamiyama et al. in 2006 [1]. Since then, considerable research efforts have been made. However, the internal quantum efficiency (IQE) of typical samples lags far behind the theoretically predicted high efficiencies, even though a large range of doping concentrations and ratios has been studied. This suggests that the IQE is severely affected by short nonradiative lifetimes.

The layers are commonly grown by the Fast Sublimation Growth Process (FSGP) [2] which is highly suitable for the growth of high quality thick epitaxial layers with reasonable growth rate. According to XRD measurements, the epitaxial layers grown by FSGP may even show an improved crystalline quality with regard to the substrate [2] and the charge carrier lifetime is usually quite high, typically about 2 µs [3]. As the considerations above indicate that short nonradiative lifetimes may be a critical issue for the light conversion efficiency of f-SiC layers, this work will focus on the role of different types of defects in fluorescent silicon carbide.

2. Experimental

2.1. *Growth of N-B co-doped 6H-SiC layers by sublimation epitaxy*

Fluorescent silicon carbide layers were grown by the FSGP with 30 min growth time and 1850 °C growth temperature on 1.4 degree off-axis 6H-SiC substrates, yielding a layer thickness of 85 ± 10 µm. A polycrystalline monolithic source co-doped with nitrogen and boron was employed.

Preface

Alternative approaches of SiC & related wide bandgap materials in light emitting & solar cell applications

Peter Wellmann[1], **Mikael Syväjärvi**[2] **and Haiyan Ou**[3]

[1]University of Erlangen-Nuremberg, Materials Department 6, Martensstr. 7, 91058
Erlangen, Germany, Phone number +49 09131 8527635,
Fax number +49 09131 8528495
[2]Linköping University, Department Physics, Chemistry and Biology, SE-58183
Linköping, Sweden, Phone number: +46 13 285708, Fax number: +46 13 142337
[3]Technical University of Denmark, Department of photonics engineering,
Building 343, Oersteds Plads, DK-2800, Kgs. Lyngby, Denmark,
Phone number: +45 4525 6374, Fax number: +45 4593 6581,

E-mail address: peter.wellmann@ww.uni-erlangen.de
E-mail address: mikael.syvajarvi@ifm.liu.se
E-mail address: haou@fotonik.dtu.dk

Materials for optoelectronics give a fascinating variety of issues to consider. Increasingly important are white light emitting diode (LED) and solar cell materials. Profound energy savings can be done by addressing new materials.

White light emitting diodes are becoming common in our lighting scene. There is a great energy saving in the transition from the light bulb to white light emitting diodes via a transition of fluorescent light tubes. However, the white LEDs still suffer from a variety of challenges in order to be in our daily use. Therefore there is a great interest in alternative lighting solutions that could be part of our daily life. All materials create challenges in fabrication. Defects reduce the efficiency of optical transitions involved in the light emitting diode materials. The donor-acceptor co-doped SiC is a potential light converter for a novel monolithic all-semiconductor white LED. In spite of considerable research, the internal quantum efficiency is far less than theoretically predicted and is likely a fascinating scientific field for studying materials growth, defects and optical transitions.

Still, efficient Si-based light source represents an ongoing research field in photonics that requires high efficiency at room temperature, wavelength tuning in a wide wavelength range, and easy integration in silicon photonic devices. In some of these devices, rare earth doped materials is considered as a potential way to provide luminescence spanning in a wide wavelength range. Divalent and trivalent oxidation states of Eu provide emitting centers in the visible region. In consideration, the use of Eu in photonics requires Eu doped thin films that are compatible with CMOS technology but for example faces material science issues like a low Eu solid solubility in silica. Therefore approaches aim to obtain efficient light emission from silicon oxycarbide which has a luminescence in the visible range and can be a host material for

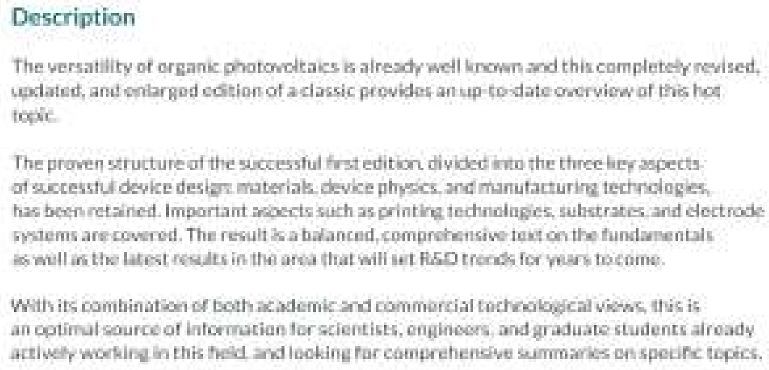
8. Books & Book Chapters

Christoph Brabec, Ulrich Scherf, Vladimir Dyakonov
Organic Photovoltaics: Materials, Device Physics, and Manufacturing Technologies: Second Edition
Wiley-VCH Verlag GmbH & Co. KGaA,
Print ISBN: 9783527332250
Online ISBN: 9783527656912

Hoth, C., Seemann, A., Steim, R., Ameri, T., Azimi, H. and Brabec, C. J.
Printed Organic Solar Cells
in Solar Cell Materials: Developing Technologies (eds G. Conibeer and A. Willoughby), John Wiley & Sons, Ltd, Chichester, UK., pp. 217-282, 2014
Print ISBN: 9780470065518
Online ISBN: 9781118695784

Organic Photovoltaics:
Materials, Device Physics, and Manufacturing Technologies,
2n Edition

Christoph Brabec (Editor), Ulrich Scherf (Editor), Vladimir Dyakonov (Editor)

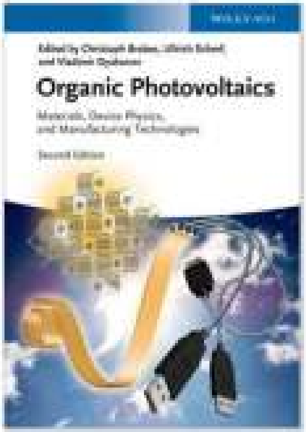


Description

The versatility of organic photovoltaics is already well known and this completely revised, updated, and enlarged edition of a classic provides an up-to-date overview of this hot topic.

The proven structure of the successful first edition, divided into the three key aspects of successful device design: materials, device physics, and manufacturing technologies, has been retained. Important aspects such as printing technologies, substrates, and electrode systems are covered. The result is a balanced, comprehensive text on the fundamentals as well as the latest results in the area that will set R&D trends for years to come.

With its combination of both academic and commercial technological views, this is an optimal source of information for scientists, engineers, and graduate students already actively working in this field, and looking for comprehensive summaries on specific topics.

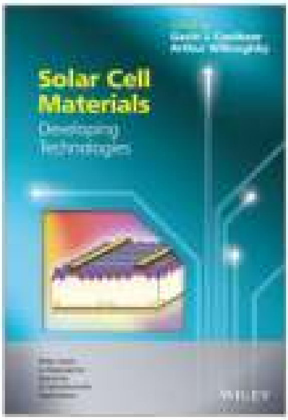


8. Printed Organic Solar Cells

Claudia Hoth, Andrea Seemann, Roland Steim, Tayebeh Ameri, Hamed Azimi and Christoph J. Brabec

Keywords:
organic photovoltaic (OPV);
organic photovoltaic (OPV) electrode requirements;
organic photovoltaic (OPV) morphology;
printed organic solar cells;
tandem technology

This chapter reviews a few of the essential technologies around the organic photovoltaic (OPV) science that are relevant for the realisation of solution-processed bulk-heterojunction solar cells. It begins with a discussion on the various aspects of morphology formation in organic bulk-heterojunction solar cells. Then, the chapter provides a review of the progress in selected interface materials, which are decisive not only for the solar cell performance but also for the long-time stability of the solar cells. Next, the chapter presents and reviews the concept of multilayer solar cells or tandem solar cells for OPV. Following this, a section explains the relevant design criteria for electrodes suitable for OPV. Finally, the chapter is concluded by a review of the overall production process, especially the printing processes for the semiconductor layer.



9. Presentations at Conferences, Workshops, Events

Ameri, Tayebeh

8 April 2014
1st progress meeting of OSNIRO (Organic Semiconductors for NIR Optoelectronics), Wuppertal, Germany
Talk: *NIR solar cell devices and modules: fabrication & characterization*

9-11 April 2014
OSNIRO Workshop 1, Academic Writing and Presentation, Wuppertal, Germany

27-30 April 2014
3rd international SolTech workshop "Solar technologies go Hybrid", Wildbad Kreuth, Germany
Poster: *IR sensitization of an indene-C60 bisadduct (ICBA) in ternary organic solar cells, device, transport and morphology investigation*

21-22 May 2014
Joint Workshop of FAU and IC on “Organic Electronics”, Erlangen, Germany

26-30 May 2014
EMRS Spring Meeting, Lille, France
Talk: *Solution-processing with non-halogenated solvents for upscaling and printing organic solar cells*
Talk: *IR sensitization of an indene-C60 bisadduct (ICBA) in ternary organic solar cells*

3-4 November 2014
ROTROT (Roll To Roll production of Organic Tandem cells), Final review, Brussels, Belgium
Talk: *WP3 Design production of tandem OPV module*

13 November 2014
Nanostructured Solar Cells (NSSC93), Tehran, Iran
Invited talk: *Organic Photovoltaics, towards a roll-to-roll printable technology*

11 December 2014
International Workshop on Organic Photovoltaics, Materials, Processing, Lifetime & Applications, Nuremberg, Germany
Poster: *IR sensitization of an indene-C60 bisadduct (ICBA) in ternary organic solar cells*

Azimi, Hamed

16 April 2014
Workshop on Nanocrystals & Film Formation, Friedrich Alexander University Erlangen-Nürnberg, Germany
Talk: *Solution processed chalcopyrite nanocrystalline solar cells*

10-13 September 2014
Solution processed Semiconductor Solar Cells (SSSC), Oxford, United Kingdom
Talk: *Effective ligand passivation of Cu_2O nanoparticles through solid-state treatment with mercaptopropionic acid*

13 November 2014
4th Conference on Nanostructured Solar Cells, Sharif University of Technology, Tehran, Iran
Invited Talk: *Low-temperature solution-processed inorganic nanocrystalline solar cells*

Brabec, Christoph J.

13 May 2014
Workshop SIEMENS & ZAE Bayern, Erlangen, Germany
F&E am ZAE BAYERN
Talk: *Technologien zur Flexibilisierung der Erneuerbaren Energien*
Gemeinsam in das neue Energiezeitalter

20 May 2014
TPE 2014, Illmenau, Germany
Invited talk: *Transparent Photovoltaics: Concepts, Materials & Technologies*

11-13 June 2014
ICOE Modena, Modena, Italy
Invited talk: *Challenges in the R2R Processing of Photovoltaics*

23 -25 June 2014
EU-DST international Workshop (LARGECELLS), Brüssel, Belgium
Invited talk: *Managing the challenges in up-scaling printed photovoltaics*
(Materials and concepts for fully printed solar cells)

07 July 2014
Treffen Die Grünen & das ZAE Bayern, Erlangen, Germany
Talk: *Aufbruch in das Erneuerbare Energiezeitalter: Forschung und Entwicklungen am ZAE Bayern. Gemeinsam in das neue Energiezeitalter*

18 August 2014
XXIII International Materials Research Congress - MRS 2014, Cancun, Mexico
Invited talk: *Alternative Concepts for a colorful OPV Technology*

12 September 2014
Tagung des Wissenschafltichen Beirats von "Smart Grid Solar”, Erlangen, Germany
Talk: *PV Forschung für das neue Energiezeitalter*

14 September 2014
GdCH Fachtagung, Jena, Germany
Invited talk: *Printed Photovoltaics “Innovation through Processing”*

17 September 2014
Imaging Illmenau 2014, Illmenau, Germany
Invited talk: *Imaging Technologies for solar energy applications*

22-25 September 2014
ISFOE Conference, Moscow, Russia
Invited talk: *Printed photovoltaics: status, concepts, materials*

25-26 September 2014
Opening ceremony of the Heeger Center, Peking, China
Invited talk: *Alternative concepts and materials for printed photovoltaics*

10 November 2014
KAUST Solar Future 2014, Thuwal, Kingdom of Saudi Arabia
Invited talk: *Closing the performance gap for printed PV technologies*

04 December 2014
MRS Fall Meeting Boston, Massachusetts
Invited talk: *Materials, concepts and architectures for printed multijunction cells*

Fecher, Frank

7-10 July 2014
7th International Symposium on Flexible Organic Electronics (ISFOE14), Thessaloniki, Greece
Talk: *Temperature simulation of shunts in OPV cells*
Talk: *Design studies of conversion efficiencies for bulk-heterojunction double- and triple-junction organic photovoltaic cells*
Talk: *Simulative comparison of grid electrode designs for ITO-free OPV modules and analysis of loss mechanisms*

17-21 August 2014
SPIE Optics + Photonics 2014, San Diego, California, USA
Talk: *Finite element simulations for studying the impact of shunts on thin film modules*

Forberich, Karen

14 May 2014
Europäische Forschungsgesellschaft Dünne Schichten e.V. (EFDS) Workshop, Dresden, Germany
Talk: Gedruckte *Nanodraht-Elektroden für optoelektronische Bauteile*

02 September 2014
2nd Euroregional Workshop on Photovoltaics EUROREG-PV 2014, Ljubljana, Slowenia
Invited talk: *Solution-processed semitransparent organic solar cells: Efficiency limits, materials and large-area processing*

03 December 2014
MRS Fall Meeting Boston, Massachusetts
Talk: *Solution-processed semitransparent organic solar cells: Efficiency limits, materials and large-area processing*

Galli, Diana

27-30 April 2014
3rd international SolTech workshop "Solar technologies go Hybrid", Wildbad Kreuth, Germany

Güldal, Sena Nusret

12-13 December 2013
SFB 953, Bad Staffelstein, Germany
Talk: *In-situ characterization methods for organic bulk-heterojunctions*

Guo, Fei

17-21 August 2014
SPIE Optics+Photonics 2014, San Diego, California, USA
Talk: *Semitransparent organic photovoltaic modules with printed silver nanowire top electrodes*

Kahmann, Simon

26-30 May 2014
E-MRS 2014 Spring Meeting, Lille, France
Talk: *Hybrid Solar Cells Using PbS Quantum dots and Narro-Bandgap Polymers*

1-6 June 2014
Ameland Summer School - Physics of Single Nano-Objects, Hollum, The Netherlands
Poster: *Hybrid Solar Cells Using PbS Quantum Dots and a Narrow-Bandgap Polymer*

Kubis, Peter

17-21 August
SPIE Optics + Photonics, San Diego, USA
Oral presentation (given by George Spyropoulos): *Patterning of OPV modules by ultra-fast laser*

Li, Ning

6-10 January 2014
Workshop for the RotRot project organized by Technical University of Denmark (DTU), Lyngby, Denmark

17 February 2014
EAM Young Researchers' Day 2014, Erlangen, Germany.
Talk: *Printing organic tandem solar cells towards 20% power conversion efficiency.*

21-25 April 2014
2014 MRS Spring Meeting & Exhibit, San Francisco, USA.
Talk*: Low-temperature, solution-processed intermediate layers for efficient organic tandem solar cells based on commercially available materials.*

11-14 May 2014
6th International Conference on HOPV, Lausanne, Switzerland.
Talk: *Towards fully printed organic tandem solar cells & modules: Development of low temperature processed intermediate layers.*

8-13 June 2014
40th IEEE PV specialists Conference, Denver, USA.
Talk*: Fully printed organic tandem cells and modules: from concepts to demonstration.*

30 June – 5 July 2014
2014 ICSM Conference, Turku, Finland.
Talk: *Towards fully printed organic tandem solar cells & modules: Development of low temperature processed intermediate layers.*

25-26 September 2014
1^{st} International Symposium on the Science of Plastic Electronics (ISSPE), Participant, Beijing, China.
Participant.

24 November – 3 December 2014
Participate in series activities organized by the Chinese Academy of Sciences.
Talk: *Fully printed organic tandem cells and modules: from concepts to demonstration.*
Scientific presentations at

- National Center for Nanoscience and Technology, Chinese Academy of Sciences (**24 November 2014,** Beijing, China)
- College of Chemistry, Chemical Engineering and Materials Science of Soochow University (**26 November 2014,** Suzhou, China)
- Printable Electronics Research Center, Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences (**27 November 2014,** Suzhou, China)
- State Key laboratory of Luminescent Materials and Devices, South China University of Technology (**2 December 2014,** Guangzhou, China)
- Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences (**3 December 2014,** Guangzhou, China)

Levchuk, Ievgen

16 April 2014
Workshop on "Nanocrystals and Film Formation" of the Research Training Group (Graduiertenkolleg) 1161/2 Disperse Systems in Electronics, Erlangen, Germany
Poster: *Nanoparticles for light down conversion*

13-18 July 2014
17th International Conference on Luminescence and Optical Spectroscopy of Condensed Matter (ICL'14), Wroclaw, Poland
Talk: *Investigation of the influence of surface passivation on the luminescence efficiency of ZnCdS:Mn/ZnS nanocrystals*

24-26 November 2014
6th EAM Symposium, Kloster Banz, Bad Staffelstein, Germany
Poster: *Highly luminescent Mn-doped alloy ZnxCd1-xS quantum dots as luminescent down-shifting layer for Si solar cells*

Richter, Moses

20-22 May 2014
TPE - Technologies for Polymer Electronics 2014, Illmenau, Germany
Poster: *Modeling the IV characteristics of an organic solar cell by TPV and CE measurements*

26-30 May 2014
E-MRS 2014 Spring Meeting, Lille, France
Talk: *Modeling the JV Characteristics of an Organic Solar Cell based on CE and TPV Measurements*

Salvador, Michael

2 September 2014
International Conference on Electroluminescence and Optoelectronic Devices, Cologne, Germany
Flash talk and poster: *A General Route to Enhance Polymer Solar Cell Performance using Plasmonic Nanoprisms*

6 October 2015
International Summit on OPV Stability, Barcelona, Spain
Talk: *Lifetime of air-processed OPVs – Aspects of Intrinsic Stability and Packaging*

15 December 2015
Gruppenseminar, AG Lupton, Universitaet Regensburg, Germany
Talk: *Strategies for enhancing the device performance of organic solar cells using colloidal*

Schimmel, Saskia

12-14 March 2014
Deutsche Kristallzüchtungstagung DKT-2014, Halle, Germany
Poster: *In Situ Visualization of GaN Crystals in Ammonothermal High Pressure Autoclaves by X-ray Imaging*

Sgobba, Vito

24 February 2014
Zwischenevaluierung-EnCN Projekt „Solarfabrik der Zukunft“-EnCN Nürnberg

Solodovnyk, Anastasiia

9-14 March 2014
SAOT Winter Academy, Oberhof, Germany
Talk: *Metamaterials with extraordinarily enhanced or suppressed transmission*

16 June 2014
BEST Summer School 2014 at EnCN, Nuremberg, Germany
Lecture: *Light Conversion Layers for Photovoltaics*

13-18 July 2014
SAOT Summer Academy,Vienna, Austria
Talk: *Physics of Fluorescence*

17-21 August 2014
SPIE Optics+Photonics 2014, San Diego, California, USA
Invited Talk: *Light Propagation in Phosphor-Filled Matrices for Photovoltaic PL Down-Shifting*
Talk: *Luminescent Down-Shifting Layers with Eu2+ and Eu3+ Doped Strontium Compound Particles for Photovoltaics*

1-3 September 2014
2nd EUROREGIONAL WORKSHOP ON PHOTOVOLTAICS: EUROREG-PV 2014, Ljubljana, Slovenia
Talk: *Light Propagation in Phosphor-Filled Matrices for Photovoltaic PL Down-Shifting*

12-13 November 2014
22. Neues Dresdner Vakuumtechnisches Kolloquium, 11. IPF-Kolloquium, 3. Workshop des Gemeinschaftsausschusses “Kombinierte Oberflächentechnik”, Dresden, Germany
Talk: *Optical Properties of Polymer Matrices Filled with PL Down-Shifting Materials for Photovoltaics*

Vetter, Andreas

8-13 June 2014
40th IEEE Photovoltaic Specialists Conference, Denver, USA
Talk: *Loss analysis on CIGS-modules by using contactless, imaging illuminated lock-in thermography and 2D electrical simulation*

11 December 2014
Workshop on Organic Photovoltaics, Nuremberg, Germany
Talk: *Quality Control of OPV Modules by IR Imaging*

Voigt, Monika

30 June -5 July 2014
ICSM 2014, Turku, Finnland
Talk: *Printed and upscaled polymer solar cells and modules by using non-halogenated solvents and via laser-ablation for structuring*

6-11 July 2014
ISFOE, Thessaloniki, Griechenland:
Talk: *Flexible upscaled and printed organic solar modules by using non-chlorinated solvents and R2R compatible methods combined with laser patterning*

Wellmann, Peter

12-14 March 2014
Deutsche Kristallzüchtungstagung DKT2014, Halle, Germany
Talk: *Sublimation Epitaxy of cubic Silicon Carbide / Sublimationsepitaktische Züchtung von kubischemSiliziumkarbid*

28 May 2014
Spring Meeting of the European Materials Reserach Society EMRS-2014, Lille, France
Invited talk*: Growth of SiC bulk crystals for application in power electronic devices*

04 June 2014
Symposium der Europäischen Forschungsgesellschaft Dünne Schichten über “Materialien für die Energietechnik - Leistungshalbleiter”, Dresden, Germany
Invited talk: *SiC bulk material and SiC on Si epitaxial layers for energy saving applications*

Wilhelm, Martin

26-30 May 2014
Spring Meeting of the European Materials Research Society E-MRS 2014, Lille, France
Talk: *Deposition of high quality 3C-SiC/Si heteroepitaxial layers at 1200°C*

Zhang, Hong

9-14 March 2014
SAOT Winter Academy, Oberhof, Germany
Talk: *The future of organic solar cells*

26-30 May 2014
EMRS Spring Meeting, Lille, France
Talk: *Solution-Processed Barium Hydroxide Modified Aluminum Doped Zinc Oxide Layer for Highly Efficient Inverted Organic Solar Cells*

13-18 July 2014
SAOT Summer Academy,Vienna, Austria
Lecture: *Solar Photovoltaic Economic Development*

Zweschke André

26-30 May 2014
Spring Meeting of the European Materials Research Society E-MRS 2014, Lille, France
Talk: *Numerical Reactive Diffusion Modeling of SEL-RTP Chalcopyrite Absorber Layer Formation*

15 December 2014, EnCN

Our annual meeting: ZAE- and i-MEET-group leader present their avtivities.

10. Seminar Presentations

Chair Seminar

28 January 2014

Wei Chen (Doctoral thesis report, i-MEET)
The Application of Up-Conversion Nanoparticles in organic solar cells

11 February 2014

Parisa Khoram (Master thesis, i-MEET)
Near-IR sensitization of organic solar cells using squaraine dyes and low band gap polymer

18 February 2014

Stefan Langner (Master thesis, i-MEET)
Encapsulation, Lifetime and Degradation Measurements of Organic Solar Cells and Modules

25 February 2014

Markus Pröll (Doctoral thesis report, ZAE)
Application Opportunities for CPCPVT Solar Collectors and Technical Barriers

15 April 2014

Stefan Raß (Bachelor thesis, i-MEET)
Entwicklung von Synthesemethoden für die Optimierung der Effizienz des $BaAl_2O_4{:}Eu^{2+}$ *Leuchtstoffs*

29 April 2014

André Hollmann (Master thesis, i-MEET)
Synthesis and characterisation of europium-doped strontium compound nanoparticles for the enhancement of solar cells via luminescent down-shifting layers

06 May 2014

Da Li (Doctoral thesis report, ZAE Bayern)
PVer dreams of solar cell

13 May 2014

Viviane Bundle (Master thesis, i-MEET)
Degradation processes on organic solar cells with FTIR

20 May 2014

Felix Fleissner (Bachelor thesis, i-MEET)
Optimization of P3HT:ICBA Solar Cells based on the Morphology Manipulation and Interface Design

Thomas Gall (Bachelor thesis, i-MEET))
Herstellung von anorganisch-organischen-Hybridlösungen

03 June 2014

Fei Guo (Doctoral thesis report, i-MEET)
Nanowires for Tandem Polymer Solar Cells

Tobias Rejek (Master thesis, i-MEET)
Plasmonic effects of silver nanoparticles in organic semiconductors

17 June 2014

Hong Zhang (Doctoral thesis report)
The interfacial modification for OPVs

Chaohong Zhang (Literature Review OPV)

01 July 2014

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

Gordana Jovicic (Doctoral thesis report, Lehrstuhl für Technische Thermodynamik)
Laser-induced phosphorescence for planar gas phase temperature and velocity measurements

08 July 2014

Derya Baran (Doctoral thesis report, i-MEET)
Smart strategies for optimization in organic solar cells without device Fabrication

Nicola Gasparini (Literature review OPV)

15 July 2014

Tobias Sauermann (Doctoral thesis report, external)
The Effect of Oxygen Induced Degradation on Charge Carrier Dynamics in Organic Solar Cells

Ramirez Quiroz César Omar (Literature review, Perovskite / or OPVs)

Derya Baran (Literature review OPV)

05 August 2014

Diana Galli (Literature review, OPVs)

09 September 2014

Wei Chen (Doctoral thesis report, i-MEET)
Application of upconversion nanophosphors for organic solar cells

18 September 2014

AmirAbbas Yousefi Amin (Master thesis, i-MEET)
Solution-based Light Electrochemical Devices with Silver Nanowire Electrodes

23 September 2014

Dominik Jordan (Bachelor thesis, i-MEET)
Solution processed lead-free organic-inorganic halide Perovskite solar cells

Stefan Langner (Literature review OPV)

30 September 2014

Jonas Boé (Master thesis, i-MEET)
Interface Modification of High Efficiency Organic Solar Cells

Jessica Gast (Bachelor thesis, i-MEET))
Influence of Refractive Indices of Matrix Material and Phosphor-Particles on Optical Properties of Down-Shifting Layers

07 October 2014

Jonas Müller (Bachelor thesis, i-MEET)
Ortsaufgelöste Messungen von Photostrom, Photo- und Elektrolumineszenz an karbazolbasierten und Perowskit-Solarzellen

Christoph Joisten (Bachelor thesis, i-MEET)
Strukturierung von Silbernanodraht-Elektroden basierend auf Laserablation mit Femtosekundenpulsen

Julian Hornich (Doctoral thesis report, i-MEET)
Simulations of solar cells with FDTD methods

14 October 2014

Bastian Schorr (Bachelor thesis, i-MEET)
Entwicklung von Entspiegelungsprozessen

28 October 2014

Anastasiia Solodovnyk (Doctoral thesis report, i-MEET)
Luminescent Down-Shifting Layers for Photovoltaics Application

Kevin Schreier (Bachelor thesis, i-MEET)
Systematische Charakterisierung von thermischen Kontaktwiderständen an Metalloberflächen

Jens Adams (Doctoral thesis final report, ZAE)
Failure analysis and long term stability of thin film solar cells and modules

04 November 2014

Carina Bronnbauer (Doctoral thesis report, i-MEET)
Printed dielectric mirrors for organic solar cells

Xiaofeng Tang (Master thesis report, i-MEET)
Design and application of novel biosensor interfaces

18 November 2014

Carina Ehrig (Doctoral thesis report, external)
Stability of photoelectrodes in photocatalysis

09 December 2014

Max Steimle (Bachelor thesis, i-MEET)
Synthesis and characterization of the core-shell $SrAl_2O_4:Eu^{2+}$, RE^{3+} *nanoparticles*

16 December 2014

Thore Bergmann (Bachelor thesis, i-MEET)
Squaraine-sensitized Ternary Solar Cells based on P3HT and PCBM

Ievgen Levchuk (Doctoral thesis report, i-MEET)
Nanosized luminescent materials as down-shifting layer for solar cells

Guest Talks

21 January 2014

Prof. Dr. Neal R. Armstrong (University of Arizona)
Interface Science of Emerging Thin Film Photovoltaic Technologies: The Role Of Interface Composition and Energetics on Charge Harvesting Efficiencies

24 February 2014

Dr. Lluís Yedra Cardona (University of Barcelona, Spain)
Electron Tomography: from HAADF to the energy-loss spectrum volume

20 March 2014

Dr. Stefanie Fladischer (Graz University of Technology, Austria)
Application of new EDXS quantification schemes in TEM to organic semiconducting devices

29 April 2014

Hyunchul Oh (Doctoral candidate, International Max Planck Research School for Advanced Materials Max Planck Institute for Intelligent Systems)
Nanoporous Materials for Hydrogen Storage and H2/D2 Isotope Separation

27 May 2014

Dr. Philip Ingenhoven (Europaeische Akademie Bozen, Institute for Renewable Energy)
Design-driven PV, Ageing and Performance Studies

24 June 2014

Dr. Christian Würth (BAM Federal Institute for Materials Research and Testin, Berlin)
Relative and absolute determination of the quantum efficiency of transparent and scattering luminescent materials

14 October 2014

Michaela Göbel (Project report, Siemens AG Healthcare Sector Imaging & Therapy Division)
Synthesis and luminescence of Gd_2O_2S *doped with rare earth ions*

04 November 2014

Dr. Pavel Troshin (Guest talk, Academy of Science, Moscow)
Overview of the research activities in OPV field at IPCP RAS

25 November 2014

Dr. Benjamin Lipovšek (University of Ljubljana, Faculty of Electrical Engineering, Laboratory of Photovoltaics and Optoelectronics, Slovenia)
Optical modelling in Photovoltaics

Shi Chen (Master thesis report (China))
Doped vanadium dioxide nanoparticles for thermochromic smart windows

16 December 2014

Dr. Chao Gao (Karlsruher Institut für Technologie)
Kesterite solar cell: open questions on material preparation and interface

11. Conferences organized by Members of the Institute

Brabec, Christoph J.

21-22 May 2014
Organizer, 1st Joint Workshop on Organic Electronics between FAU Erlangen-Nürnberg and Imperial College London, Erlangen, Germany

11 December 2014
Organizer, International Workshop on Organic Photovoltaics, Materials, Processing, Lifetime & Applications, Nuremberg, Germany

Wellmann, Peter

12-14 March 2014
Programm-Komitee Deutsche Kristallzüchtungstagung DKT-2014, Halle an der Saale, Germany

21-15 September
Programm-Komitee European Conference on Silicon Carbide and Related Materials ECSCRM-2014, Grenoble, France

12. Cooperation in Committees

Brabec, Christoph J.

EnCN – Deputy Spokesman, Member of the Academic Heads, Member of the Steering Committee

EnCN – Member of the Board of Directors

Editor of *“Journal of Photonics for Energy”* (SPIE)

Chairman of the Editorial Board *“Advanced Energy Materials”*, Wiley VCH

Editorial Board of *“Progress in Photovoltaics”*, Wiley VCH

Editorial Board of *“Emerging Materials Research”*, ice publishing

Editorial Board of the Online-Journal *“Future Photovoltaics”*, Mazik Media

Editorial Board of *“Emerging Materials Science”*,

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

Principal Investigator of the Erlangen Cluster of Excellence *"Engineering of Advanced Materials"*

Principal Investigator of the *“Optical Materials and Systems“*

Member of Scientific Board of the PE graduate school, Imperial College, London

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

Member Scientific Evaluation Committee Holst Center, Eindhoven, The Netherlands

Chairman of the Bavarian Center for Applied Energy Research

Chen, Wei

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

Hou, Yi

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

Kubis, Peter

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

Li, Ning

Member of the Organizing Committee of the EAM Young Researcher’s Day (YRD)

Member of Institute of Electrical and Electronics Engineers (IEEE)

Member of IEEE Electron Devices Society

Solodovnyk, Anastasiia

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

3rd doctoral canditate representative in Graduate School in Advanced Optical Technologies (SOAT) Friedrich-Alexander-Universität Erlangen-Nürnberg (elected for 2 years)

Wellmann, Peter

Member of the Exectuve Committee of the European Materials Research Society (EMRS).

Treasurer of the German Crystal Growth Association (DGKK e.V.)

Head of the Division *“Growth and Characterization of Semiconductor Crsytals”* of the German Crystal Growth Association DGKK e.V.

Zhang, Hong

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

13. Research Projects

Advanced Optical Technologies (SAOT) (Germany)
January 2013 – December 2014

Advanced Optical Technologies (SAOT) (Germany)
July 2014 – June 2015
Light Propagation in Phosphor-Filled Layers for Photovoltaic Application

Bayerische Forschungsstiftung, AZ-1006-11 (Germany)
July 2012 – June 2015
Intelligenz im Solarglas

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

BAYER Technology Services SolTech (Germany)
2012 – 2017
Solar technologies go hybrid
Cluster of Excellence "*Engineering of Advanced Materials*"
University of Erlangen-Nürnberg (EAM), funded by DFG Solarfabrik

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. 201206820002
Inorganic/Organic light conversion composite for organic photovoltaic application (Chen, Wei)

CSC grant No. 2011613029
Semitransparent organic solar cells (Guo, Fei)

CSC grant No. 201206130055
Design and Fabrication of organic solar cells based on solution-processed small molecules (Ke, Lili)

CSC grant No. 2011643004
Solution-processed small molecule bulk heterojunction organic solar cells (Min, Jie)

CSC grant No. 201204910209
The Interfacial Layer of Organic Solar Cells (Zhang, Hong)

CUT (Cyprus)
01 November 2010 – 31 October 2014
Molecular Electronics and Photonics

DFG SPP 1355 BR 4031/2-1 and 2-2 (Germany)
01 September 2010 – 26 June 2015
Elementarprozesse der organischen Photovoltaik:
Controlling the electronic interface properties in polymer-fullerene bulk-heterojunction solar cells.

DFG WE 210/6-1 (Germany)
01 July 2011 – 30 June 2014
In situ Visualisierung des ammonothermalen Kristallisationsprozesses mittels Röntgentechnik

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

EU RotRot FP7-ICT (grant no. 288565) (Germany)
01 September 2011 – 31 August 2014
Roll to Roll Production of Organic Tandem Cells

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

Exzellenzcluster: BTS (B-SP A7) (Germany)
01 July 2010 – 30 September 2014
Bauteile und Charakterisierung

GRK1161/2 (Germany)
01 November 2011 – 31 October 2014
Kristallisation nanopartikulärer Halbleiter-Materialien

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

Österreichische Forschungsförderungsgesellschaft mbH. FFG (Austria)
November 2011 – October 2014
Inspection tools for Solar-Technology (InSolTech)

OSNIRO FP7-PEOPLE-2013-ITN (Germany)
01 October 2013 – 31 December 2017
Organic Semiconductors for NIR Optoelectronics

SFB 953 B01 (Germany)
01 January 2012 – 31 December 2015
Synthetic Carbon Allotropes

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

TUBITAK (Turkey)
16 August 2013 – 15 August 2014
(Capan, Asli)

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

14. Teaching

Winter Term 2013/2014

Lectures (VORL)

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

Materialien der Elektronik und Energietechnik, *P. Wellmann*

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

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

Physikalische Grundlagen und Anwendungen der zerstörungsfreien Werkstoffprüfung, *S. Kasperl*

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 NT, *M. Batentschuk*

Praktikum Materialien der Elektronik und Energietechnik [PR2-ET], *P. Wellmann*

Praktikum Wahlfach Crystal Growth, *P. Wellmann*

Praktikum Werkstoffe 2 [PW2], *M. Batentschuk*

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

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

Seminars (AWA, SEM)

Anleitung zur wissenschaftlichen Arbeit, *T. Ameri*

Kern-/ Nebenfachseminar i-MEET (für Studierende im 2. MA-Semester) [SEM], *Ch. J. Brabec, E. Meißner*

Neuere Fragen zu Werkstoffen der Elektronik und Energietechnik (Lehrstuhl-Seminar), *Ch. J. Brabec, M. Batentschuk, P. Wellmann*

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

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

Seminar über spezielle Probleme der MEET, *Ch. J. Brabec, M. Batentschuk*

Summer Term 2014

Lectures (VORL)

Devices, *Ch. J. Brabec, J. Zaumseil, T. Ameri*

Elektrische, magnetische, optische Eigenschaften, *A. Winnacker, M. Batentschuk*

Elektronische Bauelemente und Materialfragen (Technologie II), *P. Wellmann*

Halbleiter großer Bandlücke, *P. Wellmann*

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

Leuchtstoffe, *M. Batentschuk*

Materialien und Bauelemente für die Optoelektronik und Energietechnologie: Anwendung [WET II], *Ch. J. Brabec*

Processing, *Ch. J. Brabec, M. Halik*

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

Werkstoffe der Elektronik in der Medizin, *M. Batentschuk, A. Winnacker*

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

Exercises and laboratory courses (EX, PJS, PR, UE)

Kernfachpraktikum I, Werkstoffe der Elektronik und Energietechnik, *M. Batentschuk*

Kernfachpraktikum II, Wahlfach Organic Electronics, *M. Batentschuk*

Lab Work Organic Electronics, *M. Batentschuk*

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

Projektarbeit - Arbeitsgemeinschaft Organische Photovoltaik (AG PV), *Ch. J. Brabec*

Seminars (SEM)

Kernfachseminar, *Ch. J. Brabec*, *M. Batentschuk*

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

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

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

Seminar über spezielle Probleme der MEET, *Ch. J. Brabec, M. Batentschuk*

Winter Term 2014/2015

Lectures (VORL)

Grundlagen der Halbleiterphysik, *W. Heiß*

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

Kolloidale Nanokristalle, *W. Heiß*

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

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

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

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 Energietechnik [PR2-ET], *P. Wellmann*

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

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

Praktikum Transporteigenschaften in HL [PrTrpeHL], *A. Osvet*

Praktikum Wahlfach Crystal Growth, *P. Wellmann*

Praktikum Werkstoffe 2 [PW2], *M. Batentschuk*

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

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

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], *Z. Rahimi, CH. Pflaum, Ch. J. Brabec*

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

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

Seminar über spezielle Probleme der MEET (Lehrstuhl-Seminar), *Ch. J. Brabec, M. Batentschuk*

15. Addresses and Maps

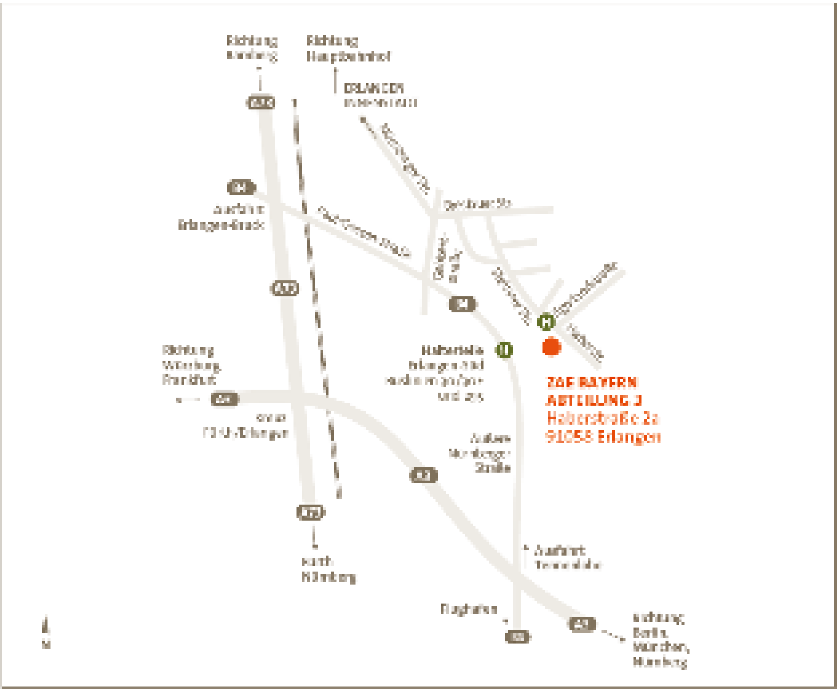
Department of Materials Science & Engineering
Materials for Electronics and Energy Technology
Friedrich-Alexander University of Erlangen-Nürnberg
Martensstr. 7
D-91058 Erlangen, Germany
Phone: +49 (0) 9131 85-27633 (Secretary)
Fax: +49 (0) 9131 85-28495
E-Mail: i-meet@ww.uni-erlangen.de
Internet: http://www.i-meet.ww.techfak.fau.de

<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.

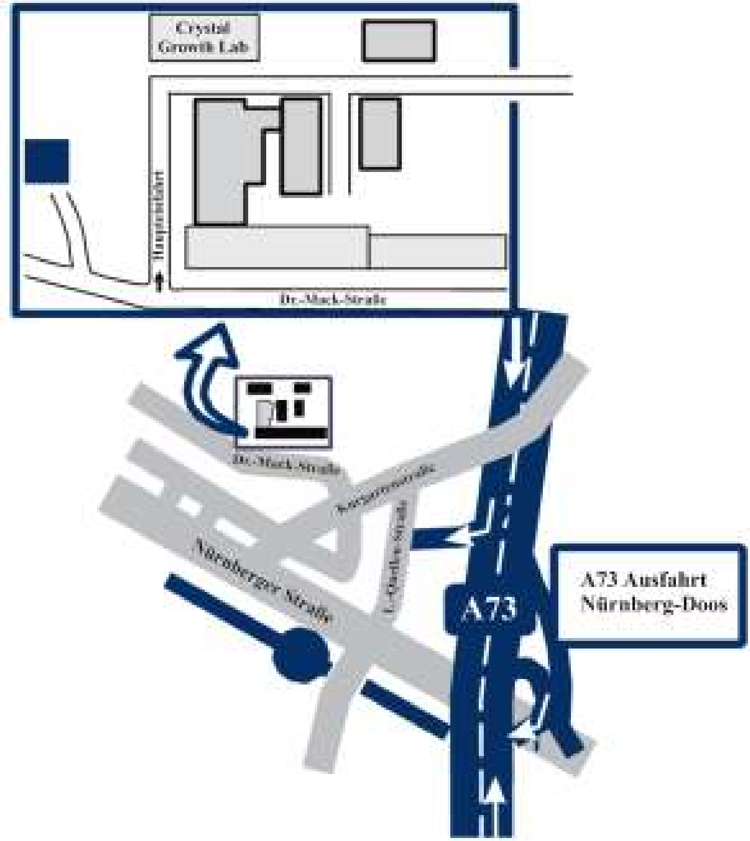
<u>By train:</u>
Railway station **Erlangen.**
Bus line No. 287 direction **"Sebaldussiedlung"**. Bus stop **"Technische Fakultät".** 50 meters to a layout plan; search for **"Insitut für Werkstoffwissenschaften"**.

ZAE Bayern Erlangen Abteilung 3

Thermosensorik und Photovoltaik
Haberstr. 2a
D-91058 Erlangen, Germany
Phone: +49 (0) 9131 / 9398 – 100
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



Geschäftsstelle Energie Campus Nürnberg e.V.
Fürther Str. 250
"Auf AEG", Gebäude 16
D-90429 Nürnberg
Phone: +49 (0) 911 / 56 854 9120
Fax: +49 (0) 911 / 56 854 9121
E-Mail: info@encn.de
Internet: http://www.encn.de