

## HL 66: Focus Session (CPP with HL): Hybrid photovoltaics and perovskites I

Time: Thursday 9:30–13:00

Location: C 130

**Invited Talk** HL 66.1 Thu 9:30 C 130  
**Advances in hybrid solar cells: From hybrid organic/inorganic to perovskite photovoltaics** — ●LUKAS SCHMIDT-MENDE — University of Konstanz

In this presentation we will discuss the path from solid-state dye sensitized solar cells over extremely thin absorber cells towards perovskite solar cells. Hybrid solar cells have been investigated for some time and a lot of knowledge gained in this field has helped to increase the power conversion efficiencies of recently discovered perovskite solar cells from 2.2% when first reported in 2006 to over 20% in 2014. Going from liquid electrolyte cells to solid-state hybrid solar cell architecture had a major influence on this performance step. Many structures previously used in hybrid solar cells have been now implemented very successfully in perovskite solar cells. We will give some examples of such knowledge transfer from conventional hybrid solar cells to perovskite solar cells. A discussion of the similarities as well as the differences of the described solar cell types will help to understand possible limitations.

HL 66.2 Thu 10:00 C 130

**Electron tomography of interpenetrating polymer/nanocrystal networks as photoactive layers in hybrid solar cells: correlations between the morphology and device performance** — ●HOLGER BORCHERT, CHRISTOPHER KRAUSE, DOROTHEA SCHEUNEMANN, and JÜRGEN PARISI — Carl von Ossietzky University of Oldenburg, Department of Physics, Energy and Semiconductor Research Laboratory, 26111 Oldenburg, Germany

Hybrid bulk heterojunction solar cells use as absorber layer an interpenetrating network of conductive polymer and inorganic semiconductor nanocrystals. Thereby, the nanomorphology of the blend layers plays an important role for the functionality of the devices. On the one hand, the absorber layer should have a large interface between both material components in order to enable efficient separation of electron-hole pairs. On the other hand, continuous pathways for electrons through the nanoparticle phase and holes through the polymer phase are required in order to enable efficient transport of the charge carriers towards the electrodes. A unique technique to investigate the three-dimensional morphology of such hybrid material layers is electron tomography, where three-dimensional images are reconstructed from a series of transmission electron micrographs recorded under different angles. In the present contribution, we investigated active layers consisting of poly(3-hexylthiophene) and colloiddally prepared copper indium disulfide nanocrystals. Correlations between the morphology of the blend layers and the electrical performance of hybrid solar cells are analyzed in dependence of varied preparation parameters.

HL 66.3 Thu 10:15 C 130

**Laser-abeted titania nanoparticles for aqueous processed hybrid solar cells** — ●VOLKER KÖRSTGENS<sup>1</sup>, STEPHAN PRÖLLER<sup>2</sup>, CHRISTOPH MAYR<sup>1</sup>, GONZALO SANTORO<sup>3</sup>, STEPHAN V. ROTH<sup>3</sup>, HRISTO IGLEV<sup>4</sup>, REINHARD KIENBERGER<sup>4</sup>, and PETER MÜLLER-BUSCHBAUM<sup>1</sup> — <sup>1</sup>TU München, Physik-Department, LS Funktionelle Materialien, James-Franck-Str. 1, 85848 Garching — <sup>2</sup>TU München, Munich School of Engineering, James-Franck-Str. 1, 85748 Garching — <sup>3</sup>DESY Photon Science, Notkestr. 85, 22607 Hamburg — <sup>4</sup>TU München, Physik-Department, LS Laser- und Röntgenphysik, James-Franck-Str. 1, 85748 Garching

Hybrid solar cells are produced by applying a new water-based processing method. The active layer consists of titanium dioxide nanoparticles produced by laser ablation in liquid and the water-soluble hole-conducting polymer poly[3-(potassium-6-hexanoate)thiophene-2,5-diyl] (P3P6T). The production of TiO<sub>2</sub> nanoparticles via laser ablation in liquid is tested with two approaches, using TiO<sub>2</sub> powder as target and a solid titanium target. The crystallinity of both components of the active layer, laser-abeted TiO<sub>2</sub> and P3P6T is investigated with X-ray diffraction (XRD) and grazing incidence wide angle X-ray scattering (GIWAXS). A key factor for the performance of the active layer is the functionalization of TiO<sub>2</sub> with the polymer P3P6T, which is probed with spectroscopic methods. The hybrid solar cells show high fill factors and open circuit voltages underlining the potential of the novel material and the environment-friendly processing method.

HL 66.4 Thu 10:30 C 130

**Junction formation and current transport mechanisms in hybrid n-Si/PEDOT:PSS solar cells** — ●SARA JÄCKLE<sup>1</sup>, MATTHIAS MATTITZA<sup>2</sup>, MANUELA GÖBELT<sup>1</sup>, and SILKE CHRISTIANSEN<sup>1,2</sup> — <sup>1</sup>Max-Planck-Institute for the Science of Light, Erlangen, Germany — <sup>2</sup>Helmholtz-Zentrum Berlin für Materialien und Energie, Berlin, Germany

Hybrid photovoltaics combining a transparent highly conductive polymer and an absorbing inorganic semiconductor promise efficient charge carrier separation and transport. We present solar cells with the 'metal'-like wide-gap polymer PEDOT:PSS and n-doped silicon archiving an open-circuit voltages up to 640mV and a power conversion efficiencies of 12%. The hybrid charge separating interface is commonly treated as a majority carrier dominated Schottky junction. Capacity- and current-voltage characteristics proof by investigating n-Si/PEDOT:PSS solar cells with varying silicon substrate doping concentrations that an inversion layer is created on the silicon surface and the charge transport is dominated by minority carriers. We will present a hybrid junction schematic explaining the promising solar cell characteristics. Furthermore possible degradation mechanisms of these hybrid solar cells under ambient conditions and the effect of encapsulation with low temperature deposited metal oxides will be discussed.

HL 66.5 Thu 10:45 C 130

**A Comparative Study of Polythiophene/c-Si Hybrid Solar Cells and Inorganic a-Si:H/c-Si Devices** — ●M. ZELLMEIER<sup>1</sup>, T. BRENNER<sup>2</sup>, S. JANIETZ<sup>3</sup>, N. H. NICKEL<sup>1</sup>, and J. RAPPICH<sup>1</sup> — <sup>1</sup>Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Institut für Silizium Photovoltaik, Kekuléstr. 5, 12489 Berlin — <sup>2</sup>University of Potsdam, Institute of Physics & Astronomy, Karl-Liebknecht-Straße 24-25, 14476 Potsdam-Golm — <sup>3</sup>Fraunhofer-Institut für Angewandte Polymerforschung (IAP), Abteilung Polymere und Elektronik, Geiselbergstr. 9, 14476 Potsdam

Non-excitonic polymer/silicon heterojunction solar cells regularly exceed power conversion efficiencies (PCE) of 10%. In combination with the possibility to use solution processing to form an electron-hole separating junction, this device type becomes highly attractive due to its potential for low cost processing. Here, we present a study in which P3HT/c-Si hybrid devices are compared to a-Si:H/c-Si heterojunctions. The advantages of the narrow absorption band of P3HT are pointed out using quantum efficiency measurements. Furthermore, the influence of the intrinsic interlayer (SiO<sub>x</sub>, Methylgroups) in the final device is investigated and directly compared to equivalent structures (SiO<sub>x</sub>, intrinsic a-Si:H) in the inorganic devices. The wafer lifetime with and without polymer was examined using quasi steady state photoconductance measurements (QSSPC) and interpreted regarding their influence on the open circuit voltage. The obtained results were used to improve the hybrid devices, leading to a high-performance hybrid solar cell with an open circuit voltage of 659 mV and a PCE of 11%.

HL 66.6 Thu 11:00 C 130

**High efficiency hybrid triple junction solar cells comprising of amorphous silicon and low band gap polymers exceeding 11 % Power Conversion Efficiency.** — ●STEFFEN ROLAND<sup>1</sup>, SEBASTIAN NEUBERT<sup>2</sup>, STEVE ALBRECHT<sup>1</sup>, BERND STANNOWSKI<sup>2</sup>, MARK SEGER<sup>3</sup>, ANTONIO FACCHETTI<sup>3</sup>, RUTGER SCHLATMANN<sup>2</sup>, BERND RECH<sup>2</sup>, and DIETER NEHER<sup>1</sup> — <sup>1</sup>University of Potsdam, Institute of Physics and Astronomie, Potsdam, Germany — <sup>2</sup>PVcomB/Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Berlin, Germany — <sup>3</sup>Polyera Corporation, Illinois, USA

Merging inorganic and organic solar cells in a series connected hybrid multi-junction is shown to be an elegant approach to prepare efficient solar cells with a total active layer thickness well below 1 μm. Complementary absorption, high absorption coefficients, and the ease of fabrication make organic low band-gap (LBG) materials, mixed with PC<sub>61</sub>BM, suitable for the use in multi-junction solar cells in combination with amorphous silicon (a-Si:H). Transfer matrix based optical modeling was employed to predict the optimum layer thicknesses of each. External quantum efficiency measurements show that all planar hybrid multi-junctions are current limited by the a-Si:H middle junction. Light scattering front contacts are used to increase the absorption and thereby currents in the amorphous silicon sub-cells. The presented multi-junction solar cells are highly efficient, showing high

open circuit voltages and high fill factors up to 80 %. Therefore, merging inorganic/organic sub-cells in multi-junction devices bears great potential as efficient, truly thin film solar cells.

### 15 min. break.

#### Invited Talk HL 66.7 Thu 11:30 C 130

**The solid state physics of hybrid perovskites** — ●JARVIST MOORE FROST<sup>1</sup>, FEDERICO BRIVIO<sup>1</sup>, KEITH BUTLER<sup>1</sup>, AURELIEN LEGUY<sup>2</sup>, ARTEM BAKULIN<sup>3</sup>, PIERS BARNES<sup>2</sup>, and ARON WALSH<sup>1</sup> — <sup>1</sup>University of Bath, Bath, United Kingdom — <sup>2</sup>Imperial College London, London, United Kingdom — <sup>3</sup>Cambridge University, United Kingdom

Hybrid perovskites offer rich solid state physics. Here we apply electronic structure techniques to develop an understanding of their intrinsically dynamic behaviour. We study the rich kinetics of the rotation of the organic cation by applying careful analysis to ab-initio molecular dynamics simulations [1]. Informed by observations of the dynamics, a on-lattice model is developed to access far longer length and timescales of the dynamic system. Parameterisation of the Hamiltonian is from electronic structure calculations. This model shows columnar anti-ferroelectric and ferroelectric ground states, as a function of strain and lattice distortion energetics. The transition from short range to long range order as a function of temperature is analysed by defining & measuring correlation functions. The electrostatic potential is reconstructed from dipole orientation. A model for polaronic transport and recombination in the material is developed, where the low electron recombination rates in these materials is related to the columnar structure of the electrostatic potential leading to electron and hole segregation.

1. J.M. Frost, K. Butler, A. Walsh, *APL Materials* 2 (8), 081506 (2014).

#### HL 66.8 Thu 12:00 C 130

**Quantum-Chemical Calculations of Hybrid Perovskites** — ●WICHARD J. D. BEENKEN, KSENIA KORSCHUNOVA, MEZHOURA OUSADOU, LARS WINTERFELD, and ERICH RUNGE — Institut für Physik und Institut für Mikro- und Nanotechnologie, Technische Universität Ilmenau, Germany

Hybrid perovskites possess a multitude of structural phases depending on temperature and the organic cations. Thus a deeper understanding of the various crystal structures and their influence on the electronic bandstructure is necessary to control the quality of these materials for solar cells. Though there exist already several structure analyses of perovskites by X-ray diffraction, the severe problem remains that the contrast of organic light atoms (C, N, H) and inorganic heavy atoms (Pb, I) is several magnitudes. This makes it difficult to determine the exact positions of the organic cations within the perovskite lattice spanned by a network of octahedral Lead-Iodide anions. Consequently, most of the published structures for hybrid perovskites do only provide guesses for the organic part, in particular for the H-atoms. Their positions, however, may be important for understanding the electronic band structure, which is also difficult to be determined experimentally, e.g. by angle resolved UPS, for the polycrystallinity of the samples. Therefore, we have done DFT calculations using the quantum-chemical package VASP 5.3 for crystal structure optimization and band structure determination of low-temperature and metastable phases of several organic-inorganic hybrid perovskites.

#### HL 66.9 Thu 12:15 C 130

**Radiative efficiency of perovskite solar cells** — ●KRISTOFER TVINGSTEDT<sup>1</sup>, OLGA MALINKIEWICZ<sup>2</sup>, ANDREAS BAUMANN<sup>3</sup>, CARSTEN DEIBEL<sup>1</sup>, HENRY J. SNAITH<sup>4</sup>, VLADIMIR DYAKONOV<sup>1,3</sup>, and HENK J. BOLINK<sup>2</sup> — <sup>1</sup>Experimental Physics VI, Julius-Maximilian University of Würzburg, 97074 Würzburg, Germany — <sup>2</sup>Instituto de Ciencia Molecular, Universidad de Valencia, 46980 Paterna, Valen-

cia, Spain — <sup>3</sup>Bavarian Center for Applied Energy Research, 97074 Würzburg, Germany — <sup>4</sup>University of Oxford, Clarendon Laboratory, Parks Road Oxford, OX1 3PU, United Kingdom

Perovskite PVs have reached significant power conversion efficiency in a very short time period. Apart from providing a rather high photocurrent, they also retain a comparatively high open circuit voltage. We here address the upper limit to open circuit voltage and power conversion efficiency for the novel type of photovoltaic cells based on methylammonium lead iodide perovskites. By accurate determination of the present solar cells radiative efficiency, that is their ability to emit light, we conclude how far these solar cells are from their own thermodynamic limit. We explain the reason for the high voltage and put it in relation to those of earlier generation photovoltaic technologies. We further highlight that, as the perovskite steady state photoluminescence is rather strong at open circuit conditions, and substantially quenched only at short circuit, they perform just as good solar cells should do, and in this respect also rather different from most OPVs or DSSC cells studied so far.

#### HL 66.10 Thu 12:30 C 130

**Recombination behaviour of hybrid perovskite thin films studied by low temperature photoluminescence** — SERGEJ LEVCENCO, AMRITA MANDAL BERA, DAN WARGULSKI, IBRAHIM SIMSEK, and ●THOMAS UNOLD — Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Hahn-Meitner Platz 1, 14109 Berlin

Hybrid organometal perovskites recently have been successfully implemented as absorber layers in high efficiency thin film solar cells. In particular the CH<sub>3</sub>NH<sub>3</sub>PbI<sub>3</sub> based materials show long minority carrier recombination lifetimes, implying a minor role of non-radiative recombination even at room temperature. In order to better understand the radiative recombination properties we have studied hybrid perovskite layers on glass, which were prepared by immersion of polycrystalline PbI<sub>2</sub>- thin films into methylammoniumiodide dissolved in isopropanol. The perovskite layers show high luminescence efficiencies at room temperature with a broad peak centered at around 1.6eV. At low temperature, several additional transitions are observed, which shift with temperature and show significant thermal quenching. Changes in the radiative emission caused by degradation of the layers under ambient conditions will also be reported.

#### HL 66.11 Thu 12:45 C 130

**Transient electrical studies probing charge carrier recombination in methylammonium lead iodide perovskite solar cells** — ●ANDREAS BAUMANN<sup>1</sup>, STEFAN VÄTH<sup>2</sup>, KRISTOFER TVINGSTEDT<sup>2</sup>, MICHAEL C. HEIBER<sup>2</sup>, CRISTINA MOMBLONA<sup>3</sup>, HENK J. BOLINK<sup>3</sup>, and VLADIMIR DYAKONOV<sup>1,2</sup> — <sup>1</sup>Bayerisches Zentrum für Angewandte Energieforschung, Am Galgenberg 87, D-97074 Würzburg — <sup>2</sup>Experimentelle Physik 6, Julius-Maximilians-Universität Würzburg, Am Hubland, D-97074 Würzburg — <sup>3</sup>Universidad de Valencia, Paterna, Spain

Organo-metal halide perovskites like methylammonium lead iodide show extraordinary photovoltaic performance with power conversion efficiencies exceeding 20%. However, a fundamental understanding of the physical processes in perovskite solar cells is still lacking but is essential for further development in this quickly emerging research field. Here, we present our recent studies on the charge carrier recombination in methylammonium lead iodide perovskite solar cells in a planar configuration without porous transport layers by means of open circuit voltage decay measurements. The results are compared with the recombination behavior in reference state-of-the-art polymer-fullerene bulk heterojunction solar cells.[1] We observed two very different time domains in the transients of the perovskite solar cells in contrast to the organic reference solar cells. We will discuss potential origins of these unique behavior and compare the results for various device configurations.[1] A. Baumann et al., *APL Mater.* 2, 081501 (2014)