

## CPP 8: Fundamentals of Perovskite Photovoltaics II (joint session CPP/DS/HL)

Time: Monday 15:00–18:15

Location: ZEU 222

**Invited Talk**

CPP 8.1 Mon 15:00 ZEU 222

**Visualizing Charge Carrier Diffusion In Hybrid Halide Perovskite Thin Films** — ●ACHIM HARTSCHUH, KATHRIN HANDLOSER, IRENE GRILL, NICOLAI HARTMANN, NADJA GIESBRECHT, MELTEM AYGÜLER, MATHIAS HANDLOSER, THOMAS BEIN, and PABLO DO-CAMPO — Department of Chemistry and CeNS, LMU Munich, 81377 Munich, Germany

Organic-inorganic metal halide perovskites represent one of the most promising classes of absorber materials for future photovoltaic applications [1]. A prerequisite for the efficient extraction of photo-generated carriers is the combination of low non-radiative relaxation rates and rapid diffusive transport. We study the excited state dynamics and charge carrier transport properties in different perovskite thin films using time-resolved photoluminescence microscopy. By scanning the confocal detection with respect to the excitation spot, we visualize diffusive transport on micrometer length scales and determine the charge carrier diffusion constants and mobilities [2]. We complement these studies by transient photocurrent measurements on the same films and derived devices [3,4].

**Invited Talk**

CPP 8.2 Mon 15:30 ZEU 222

**Photon recycling in hybrid lead-halide perovskite semiconductors** — ●FELIX DESCHLER — University of Cambridge, Cambridge, UK

We discuss the effect of photon recycling on the externally measured radiative recombination rates in hybrid perovskites. By combining transient absorption with transient photoluminescence (PL) data, we distinguish radiative from non-radiative processes and find that the PL originates from a bimolecular process for all investigated carrier densities. We measure external photoluminescence quantum efficiencies (PLQEs) under continuous-wave and pulsed excitation. Taking into account photon recycling, we connect the externally measured radiative efficiencies with the actual internal values, and derive internal PLQEs exceeding 80%.

We map the propagation of photo-generated luminescence and charges from a local photo-excitation spot in thin films of lead triiodide perovskites using a confocal microscopy setup. We observed regenerated PL emission at distances as far as 50 micrometers away from photo-excitation. We map the internal photon distribution in the film and find that, over these distances, the peak of the internal photon spectrum red-shifts from 765 to >800 nanometers. We build a lateral-contact solar cell with selective electron- and hole-collecting contacts, using a combination of photo-lithography and electro-deposition. We used these devices as a platform to study photocurrent propagation and found that charge extraction can be achieved well beyond 50 micrometers away from the excitation.

CPP 8.3 Mon 16:00 ZEU 222

**Coherent Dynamics of Free Exciton Dissociation in Lead-iodide Perovskites observed by 2D Electronic Spectroscopy** — ●AJAY JHA<sup>1</sup>, HONG-GUANG DUAN<sup>1,2,3</sup>, VANDANA TIWARI<sup>1</sup>, PABITRA NAYAK<sup>4</sup>, MICHAEL THORWART<sup>2,3</sup>, HENRY J. SNAITH<sup>4</sup>, and R. J. DWAYNE MILLER<sup>1,3,5</sup> — <sup>1</sup>MPI-Structure & Dynamics of Matter, Hamburg, Germany — <sup>2</sup>Universität Hamburg, Germany — <sup>3</sup>CUI Hamburg, Germany — <sup>4</sup>University of Oxford, UK — <sup>5</sup>University of Toronto, Canada

Hybrid organolead halide perovskites with high carrier mobility and large dielectric constant have received considerable attention as an excellent material for low-cost efficient photovoltaics. The power conversion efficiency of perovskite based solar cells has meteorically advanced to 22.1% with excitonic dye-sensitization concept and ~15% for planar heterojunction configuration. The unprecedented success of this material demands the fundamental understanding of underlying microscopic mechanisms for photoinduced charge generation. Recent studies suggest that most photoexcitations in perovskite are free charge carriers behaving like III-V inorganic semiconductors, but the contribution of excitons has been a matter of debate. We have employed ultrafast 2D electronic spectroscopy to probe elementary optical excitation of CH<sub>3</sub>NH<sub>3</sub>PbI<sub>3</sub> thin films. We distinctly observe the electronically coupled excitonic and free carrier transitions at room temperature. We captured an ultrafast exciton dissociation favored by low exciton binding energy of ~40 meV. The interplay of strongly coupled dominant

vibrational mode to exciton dynamics will also be discussed.

CPP 8.4 Mon 16:15 ZEU 222

**Time Resolved Microwave Conductivity on Perovskites** — ●MARVIN GRÜNE<sup>1</sup>, ANDREAS SPERLICH<sup>1</sup>, ANDREAS BAUMANN<sup>2</sup>, and VLADIMIR DYAKONOV<sup>1,2</sup> — <sup>1</sup>Experimental Physics VI, Julius Maximilian University of Würzburg, 97074 Würzburg — <sup>2</sup>ZAE Bayern, 97074 Würzburg

Organo-metal halide perovskites continue to be the star of thin film solar cells exhibiting rapidly rising power conversion efficiencies. For further improvement of these solar cells it is essential to understand the fundamental intrinsic properties like photoconductivity, recombination and charge carrier mobility. Therefore, we investigate the mixed halide perovskite layers of CH<sub>3</sub>NH<sub>3</sub>PbX<sub>3</sub> (X: I<sup>-</sup>, Br<sup>-</sup> and Cl<sup>-</sup>) using time-resolved microwave conductivity. With this contactless measurement technique we address the charge carrier lifetime, decay kinetics and intrinsic mobility of perovskite structures with different halide substituents X. The mobility increases more than a factor of 2 in this order of substituents up to 8 cm<sup>2</sup>/Vs. Furthermore, the influence of solvent annealing on the crystallization process of the CH<sub>3</sub>NH<sub>3</sub>PbI<sub>3</sub> film has been investigated, now considering temperature dependence. This crystallization method generates e.g. bigger crystal domain sizes and almost one order of magnitude higher mobilities. Due to the absence of transport layers, we can relate differences in the results to intrinsic properties of the perovskite layers. Solar cells with the investigated layer achieve up to 16% efficiency in our labs.

**15 min break****Invited Talk**

CPP 8.5 Mon 16:45 ZEU 222

**Interface engineering: the route towards high efficiency and stable hybrid perovskite solar cells** — ●GIULIA GRANCINI — Group for Molecular Engineering of Functional Materials, EPFL Valais Wallis, CH-1951 Sion, Switzerland

Hybrid perovskite solar cells are undoubtedly leading the photovoltaic scene with their power conversion efficiency (PCE) >22%. Tuning the material composition, i.e. by cations and anions substitution (e.g. introducing a small amount of Br) and the interfacial properties, optimizing the structural and chemical interactions and the optoelectronic processes therein have been the successful routes for a real breakthrough in device efficiency and reproducibility. However, despite the impressive PCE reported, hybrid perovskite suffer of severe instability mainly due to material degradation upon exposure to water and moisture further accelerated under local heating and UV irradiation. Diverse technological approaches have been proposed delivering appreciable improvements, but still failing by far the market requirements. Recently, we pioneered a new concept by interface engineering a multi-dimensional composite of two dimensional (2D) (HOOC(CH<sub>2</sub>)<sub>2</sub>NH<sub>3</sub>)<sub>2</sub>PbI<sub>4</sub> / 3D-CH<sub>3</sub>NH<sub>3</sub>PbI<sub>3</sub> perovskite molecular junction. The composite forms an exceptional gradually organized structure that yields up to 12.9% PCE. Aiming at the up-scaling of this technology, we realize 10x10 cm<sup>2</sup> large-area solar modules by a fully printable, industrial-scale process delivering 11.2% stable devices for 9,000 hours under accelerated testing conditions, leading to a record one-year stability.

CPP 8.6 Mon 17:15 ZEU 222

**Characterization of perovskite solar cells: Towards a reliable measurement protocol** — ●EUGEN ZIMMERMANN<sup>1</sup>, KA KAN WONG<sup>1</sup>, MICHAEL MÜLLER<sup>1</sup>, HAO HU<sup>1</sup>, PHILIPP EHRENREICH<sup>1</sup>, MARKUS KOHLSTÄDT<sup>2,3</sup>, ULI WÜRFEL<sup>2,3</sup>, SIMONE MASTROIANNI<sup>2</sup>, GAYATHRI MATHIAZHAGAN<sup>2</sup>, ANDREAS HINSCH<sup>2</sup>, TANAJI P. GUJAR<sup>4</sup>, MUKUNDAN THELAKKAT<sup>4</sup>, THOMAS PFADLER<sup>1</sup>, and LUKAS SCHMIDT-MENDE<sup>1</sup> — <sup>1</sup>Universität Konstanz, Konstanz, Germany — <sup>2</sup>Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany — <sup>3</sup>Freiburg Materials Research Center FMF, University of Freiburg, Freiburg, Germany — <sup>4</sup>Applied Functional Polymers, Department of Macromolecular Chemistry I, University of Bayreuth, Bayreuth, Germany

Tremendous progress on power conversion efficiency of lead halide perovskite solar cells during the last few years drastically increased the interest in research on this material. However, a so called "hysteretic" behaviour during current density-voltage (J-V) measurements is dif-

ferently severe for differently prepared solar cells and strongly depends on scan parameters like scan rate, and measurement history. This challenges reliable results across different laboratories and hinders the aspect of commercialization. Here, we propose a reliable measurement protocol by introducing stabilized device characteristics obtained from an adaptive tracking of the maximum power point and the open circuit voltage, and compare such obtained values to device characteristics derived from standard and time resolved J-V measurements for varying solar cells fabricated in different laboratories.

CPP 8.7 Mon 17:30 ZEU 222

**Removing leakage recombination current in planar perovskite solar cells** — ●KRISTOFER TVINGSTEDT<sup>1</sup>, LIDON GIL-ESCRIG<sup>2</sup>, CHRISTINA MOMBLONA<sup>2</sup>, PHILIPP RIEDER<sup>1</sup>, DAVID KIEMASCH<sup>1</sup>, ANDREAS BAUMANN<sup>3</sup>, HENK J. BOLINK<sup>2</sup>, and VLADIMIR DYAKONOV<sup>1,3</sup> — <sup>1</sup>Experimental Physics VI, Julius Maximilian University of Würzburg, 97074 Würzburg — <sup>2</sup>Instituto de Ciencia Molecular, Universidad de Valencia, C/Catedrático J. Beltrán 2, 46980 Paterna, Spain — <sup>3</sup>Bavarian Center for Applied Energy Research 97074 Würzburg

All solar cells, including perovskites, suffer from recombination mechanisms of various types out of which leakage current usually dominates at lower voltages. Herein, we demonstrate a three order reduction of this recombination loss mechanism in planar perovskite solar cells by replacing the commonly used hole selective electrode PEDOT:PSS with a polymer arylamine hole transporting semiconductor. This renders these solar cells more useful under lower light intensity, such as end of the day and indoor conditions which we demonstrate via the extreme case of moon lighting conditions, where the cells still generates open circuit voltages of 530 mV. By this substantial leakage reduction we can be able to confirm charges to also remain in the photovoltaic device for up to 2 hours after the light has been switched off. We discuss the mechanisms behind this feature and explain why the arylamine is a superior hole selective electrode.

CPP 8.8 Mon 17:45 ZEU 222

**Double-layer charge selective contacts in perovskite solar cells as a key to improved efficiency and reduced hysteresis effects** — ●LUKAS KEGELMANN<sup>1</sup>, CHRISTIAN WOLFF<sup>3</sup>, CELLINE AWINO OMONDI<sup>1</sup>, LARS KORTE<sup>1</sup>, THOMAS DITTRICH<sup>1</sup>, DIETER NEHER<sup>3</sup>, BERND RECH<sup>1</sup>, and STEVE ALBRECHT<sup>2</sup> — <sup>1</sup>Helmholtz-Zentrum Berlin, Inst. for Silicon Photovoltaics, Berlin, 12489, Germany. — <sup>2</sup>Helmholtz-Zentrum Berlin, Young Investigator Group Perovskite

Tandem Solar Cells, Berlin, 12489, Germany. — <sup>3</sup>University of Potsdam, Soft Matter Physics, Potsdam, 14476, Germany.

Planar low-temperature processed perovskite solar cells without a mesoscopic scaffold are advantageous for a possible large-scale production but often suffer from photocurrent hysteresis, especially in the regular 'n-i-p'-structure. Here, we systematically study the influence of different low-temperature deposited electron transport materials (ETM) on planar regular solar cell characteristics. We further show that an elaborately chosen metal oxide interlayer in an ITO/metal oxide/PCBM double-layer ETM can significantly improve the device performance. J-V measurements reveal substantial reductions of hysteresis effects and enhanced power conversion efficiencies up to a champion stabilized value of 18.0 % for TiO<sub>2</sub> interlayers. Surface photovoltage spectroscopy is used to show comparable absorber qualities on all ETMs for the fabrication process used here. Additionally, improved hole blocking for the double-layer structure is suggested by UPS and the metal oxide interlayer is considered to reduce shunt paths as it hampers direct contact between perovskite and the ITO electrode.

CPP 8.9 Mon 18:00 ZEU 222

**Electrical impedance spectroscopy on perovskite solar cells** — ●FISCHER MATHIAS<sup>1</sup>, DAVID KIEMASCH<sup>1</sup>, VLADIMIR DYAKONOV<sup>1,2</sup>, and ANDREAS BAUMANN<sup>2</sup> — <sup>1</sup>Experimental Physics VI, Julius Maximilian University of Würzburg, 97074 Würzburg — <sup>2</sup>Bavarian Center for Applied Energy Research, 97074 Würzburg

Electrical impedance spectroscopy has shown to be a powerful technique to obtain informations about key parameters of a solar cell, like series and recombination resistance, build-in potential and the dielectric constant. Here, we performed impedance measurements over a wide temperature range from 300K down to 150K on solution processed CH<sub>3</sub>NH<sub>3</sub>PbI<sub>3</sub> perovskite solar cells. We compared the impedance spectra of n-i-p and p-i-n device configuration which is FTO/TiO<sub>2</sub>/Perovskite/Spiro-MeOTAD/Au and ITO/PEDOT:PSS/Perovskite/PC<sub>60</sub>BM/C<sub>60</sub>/BCP/Au, respectively. We fit the impedance spectra by using corresponding equivalent circuits to investigate the dielectric behavior depending on the cell layout and preparation technique. We compare the extracted time constants at different frequency domains to reveal the influence from the p- and n-layer materials on the photovoltaic properties of the perovskite absorber material itself and examined charge carrier recombination behavior in dependency of illumination intensity.