# Metal-oxide based charge extraction and recombination layers for organic solar cells

Thomas Riedl
Institute of Electronic Devices, University of Wuppertal, Germany

Substantial progress in the field of organic solar cells (OSCs) has pushed the device efficiency to levels of 12%. Aside from improvements in the design and synthesis of active materials for OSCs, interface engineering has emerged as a key to increased efficiency and device stability. For facilitated charge extraction, the energy levels at the interface between the electrodes and the photo-active materials must be matched properly. To this end, particular charge extraction interlayers can be employed.

On the cathode side, zinc oxide (ZnO) is a well-established electron extraction layer (EEL). A somewhat general phenomenon that comes with the use of these EELs is the requirement of UV activation to render the solar cells highly efficient.[1] I will show how electrically doped or plasmonically sensitized metal oxides can be used to overcome this unwanted procedure.[2-3] A common feature of ZnO-based EELs (doped or non-doped) is the appearance of photo-shunts upon prolonged UV exposure and the concomitant decay of $V_{oc}$ and *FF*.[4] I will discuss the underlying mechanisms, and I will show that this issue can be mitigated by the use of tin oxide ($SnO_x$) as EEL. $SnO_x$ is chemically extremely robust and as an EEL does not require any UV activation.[5] The surface properties of $SnO_x$ in comparison to ZnO will be discussed.

In the second part, I will present the first all-oxide interconnect for organic tandem cells, which is based on a bilayer of a high work-function (WF) metal-oxide (e.g. $MoO_x$ or $VO_x$) and the low WF $SnO_x$. Using photo-electron spectroscopy and Kelvin probe analysis, we unveil the electronic line-up at the interface of $MoO_x$ and $SnO_x$. The working principle of these interconnects in tandem cells will be discussed.

[1] H. Schmidt, K. Zilberberg, S. Schmale, H. Flugge, T. Riedl, W. Kowalsky, Appl Phys Lett 2010, 96, 243305.
[2] S. Trost, K. Zilberberg, A. Behrendt, A. Polywka, P. Görrn, P. Reckers, J. Maibach, T. Mayer, T. Riedl, Advanced Energy Materials 2013, 3, 1437.
[3] S. Trost, T. Becker, K. Zilberberg, A. Behrendt, A. Polywka, R. Heiderhoff, P. Görrn, T. Riedl, Scientific Reports 2015, 5, 7765.
[4] A. Manor, E. A. Katz, T. Tromholt, F. C. Krebs, Advanced Energy Materials 2011, 1, 836.
[5] S. Trost, A. Behrendt, T. Becker, A. Polywka, P. Görrn, T. Riedl, Advanced Energy Materials 2015, 5, 1500277.

# TCO-based infrared plasmonics and hyperbolic metamaterials

Sascha Kalusniak, Laura Orphal, Peter Schäfer and Sergey Sadofev
Department of Physics, Humboldt-Universität zu Berlin, Germany

The interaction of metals with electromagnetic radiation gives rise to collective charge excitations called surface plasmon polaritons. The potential of these coupled light-matter states for creating nano-scale photon-based circuits is the core of what is summarized today by the term "plasmonics". We will show that strongly n-type doped ZnO and In2O3 are excellent plasmonic materials in the infrared spectral range. Using molecular beam epitaxy, we are able to generate free carrier concentrations beyond 1021 cm-3 without significant deterioration of the crystal perfection. In this way, a metallic dielectric function is formed with a negative-to-positive crossover of the real part tunable from mid infrared up to telecommunication wavelengths. The losses are at least one order of magnitude lower than for traditional metals. Moreover, the controllable stacking of alternate subwavelength-thin metallic and dielectric oxide layers in a multilayer structure opens a direct route for realization of hyperbolic metamaterials, i.e. effective uniaxial crystals, where the electrical permittivity parallel and perpendicular to the crystal axis have opposite sign. As a consequence, the normally elliptic isofrequency curves of the extraordinary wave are transformed into a hyperboloid and the material provides an access to wave vector states far exceeding that of free-space. We demonstrate realization of metal-oxide based hyperbolic medium at wavelength of 1.5 μm and discuss a potential integration of an organic emitter layer in the spectral range of interest.