HL 5: Photovoltaic

Time: Monday 10:15–13:15 Location: POT 151

HL 5.1 Mon 10:15 POT 151

Spatially resolved photoluminescence measurements for a comparative analysis of $CuInS_2$ and $Cu(In,Ga)S_2$ thin films — •Florian Heidemann[1], Levent Gütay[1], Rudolf Brüggemann[1], Saoussen Merdes[3], Alexander Meeder[2], and Gottfried H. Bauer[1] — [1]Institute of Physics, CvO University Oldenburg, Germany — [2]SULFURCELL Solartechnik GmbH, Berlin, Germany — [3]Helmholtz-Zentrum Berlin, Germany

At present chalcopyrite semiconductors like $Cu(In,Ga)Se_2$ and $Cu(In,Ga)S_2$ are most promising absorbers for thin film solar cells. Due to their grainy structure and inhomogeneous growth they show considerable degrees of spatial inhomogeneities in structural, optical and optoelectronic properties in the length scale of grain sizes. To analyze these locally fluctuating magnitudes we have performed spectrally resolved luminescence measurements with a high lateral resolution ($\leq 1\mu$m) in a confocal microscope setup. This makes the determination of the spatial variation in the splitting of the quasi-Fermi levels ($\mu = E_{Fn} - E_{Fp}$) as well as the local absorbance of the material possible. A comparison of these properties, which are crucial for the solar light conversion efficiency, is made for $CuInS_2$ and $Cu(In,Ga)S_2$ absorber layers for data obtained from statistically representative scan areas. The results show that an increase in bandgap and the mean μ due to an incorporation of gallium does not come along with a decrease in the variation of μ over the absorber layer. A quantification of the lateral patterns of constant μ by Minkowski-operations indicates similar pattern sizes in the range of a few μm for the analyzed samples.

HL 5.2 Mon 10:30 POT 151

Diffusion processes and chemical changes at the (Zn,Mg)O/ $CuIn(S,Se)_2$ interface caused by RF magnetron sputtering deposition — •Felix Erfurth[1], Benjamin Hussmann[1], Lothar Weinhardt[1], Achim Schöll[1], Friedrich Reinert[1], Eberhard Umbach[1,2], Thomas Niesen[3], Jörg Palm[3], Sven Visbeck[3], Alexander Grimm[4], Iver Lauermann[4], and Reiner Klenk[4] — [1]Universität Würzburg, Experimentelle Physik II, 97074 Würzburg — [2]Forschungszentrum Karlsruhe GmbH, 76133 Karlsruhe — [3]Avancis GmbH & Co. KG, 81739 München — [4]Helmholtz Zentrum Berlin für Materialien und Energie, 14109 Berlin

(Zn,Mg)O buffer layers on $Cu(In,Ga)(S,Se)_2$ thin film solar cells are a promising alternative to CdS buffer layers. Although in the past the radio frequency magnetron sputtering deposition on (Zn,Mg)O has been empirically optimized to reach high efficiencies, only little is known about the influence of the sputter parameters on the electronic and chemical structure of the absorber/buffer interface. We have used in-situ X-ray Photoelectron Spectroscopy (XPS) and X-ray induced Auger Electron Spectroscopy (XAES) to analyze the influence of different sputter parameters and to compare samples prepared by different groups.

All samples show the formation of indium oxide and zinc - sulfur/selenide bonds at the buffer/absorber interface. Moreover, the hydroxide/oxide ratio at the interface is strongly increased as compared to the respective ratio in the bulk. Further studies showed a diffusion of sodium to the surface for thin (Zn,Mg)O layers.

HL 5.3 Mon 10:45 POT 151

Mikroskopische Lumineszenzeigenschaften von polykristallinen $CuInS_2$-Dünnschichten — •Anja Dempewolf[1], Frank Bertram[1], Alexander Franke[1], Thomas Hempel[1], Jürgen Christen[1], Joachim Klaer[2], Frank Wünsch[2] und Thomas Schedel-Niedrig[2] — [1]Institut für Experimentelle Physik, Otto-von-Guericke-Universität Magdeburg — [2]Helmholtz-Zentrum Berlin für Materialien und Energie

Die Lumineszenzeigenschaften von sowohl unpassivierten als auch Si_xN- und ZnO/CdS-passivierten polykristallinen $CuInS_2$-Dünnschichten (CIS) für die Anwendung als Absorbermaterial in Solarzellen wurden mittels orts-, zeit- und spektral aufgelöster Kathodolumineszenz (KL) und spektral aufgelöster Photolumineszenz (PL) untersucht. Die auf einem Glassubstrat mit gesputtertem Mo-Kontakt durch ein RTP-Verfahren *(rapid thermal processing)* hergestellten CIS-Schichten besitzen eine Dicke von etwa 2,1 μm und weisen eine körnige Oberflächenmorphologie auf. Das integrale Tieftemperatur-KL-Spektrum (5 K) des CIS wird durch eine exzitonische Lumineszenz um 1,5 eV dominiert. In lokal aufgelösten Spektren lässt sich in einem Energiebereich von 1,35 eV bis 1,56 eV eine Vielzahl von einzelnen Emissionslinien identifizieren, die vor allem gebundenen Exzitonen und Donator-Akzeptor-Übergängen zugeschrieben werden. Allgemein zeigen die untersuchten Schichten in der Intensität und Emissionsenergie eine inhomogene Lumineszenzverteilung. So weichen die Lumineszenzeigenschaften individueller Körner als auch verschiedener Facetten eines einzelnen Korns signifikant voneinander ab.

HL 5.4 Mon 11:00 POT 151

Spectral Response of $CuIn_{1-x}Ga_xSe_2$ Heterodiodes Operated at Constant V_{OC} and Constant I_{SC} Compared with Traditionally Recorded Spectral Quantum Yield — •Sven Burdorf, Rudolf Brüggemann, and Gottfried Heinrich Bauer — Institute of Physics, Carl von Ossietzky University Oldenburg D-26111 Oldenburg, F.R. Germany

Traditional spectral response experiments in solar cells, such as quantum yields show the dependence of the excess carrier contribution and respective recombination on the depth of the device in terms of the profile of the optical generation. However, this depth information is masked by the condition of current continuity that is met by contributions of minority as well as majority carriers across the entire depth of the device and commonly the information on local properties is not reflected straightforwardly. In our approach - analogously to the concept of the constant photocurrent method (CPM) - we have adjusted either constant V_{OC} (c-Voc) or I_{SC} (c-Isc) by recording the spectral photon fluxes necessary for these conditions. In particular in Voc operation excess carriers recombine exclusively within the device and thus the signal is more sensitive against recombination. Our results of the c-Voc and c-Isc experiments for CIGSe-heterodiodes show significant differences particularly in the short-wavelength regimes. The comparison of experimental results with numerical modeling shows that this difference is growing larger with increasing interface recombination.

15 min. break

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Performance of InGaAsP/InGaAs tandem solar cells with an InGaAs/GaAsSb tunnel junction — •Erol Sagol, Nadine Szabo, Ulf Seidel, Christian Höhn, Klaus Schwarzburg, and Thomas Hannappel — Helmholtz-Zentrum Berlin, Glienicker Str. 100, 14109 Berlin-Germany

Three types of state-of-the-art III-V triple-junction solar cells have already surpassed the 40% efficiency mark, despite having non-optimized band gaps. But still considerably higher efficiencies can be achieved with a four-junction configuration, which has optimized band gaps around 1.9, 1.4, 1.0 and 0.7 eV. This can be realized with a mechanically stacked GaAs-based GaInP/GaAs tandem and an InP-based InGaAsP/InGaAs tandem cell. For this purpose, we grew InGaAsP/InGaAs tandem solar cells lattice-matched to InP by MOVPE. The InGaAs bottom cell (0.73 eV) and the InGaAsP top cell (1.03 eV) were connected with a tunnel junction, which was composed of highly doped n-InGaAs and p-GaAsSb layers. In order to evaluate the performance of the tunnel junction, separate devices were grown without the photoactive layers. High current densities of several thousand A/cm2 were achieved already in the bias regime of several 100 mV. Hence, voltage losses in the tunnel diode should not be of concern for the solar cell even under extreme concentration ratios (> 1000 suns). Our results show that the contribution of such a low band gap InGaAsP/InGaAs tandem bottom cell, reaching efficiencies above 10% under GaAs, is considerably higher than a conventional germanium subcell.

HL 5.6 Mon 11:45 POT 151

3D photonic crystal interlayers for mircomorph thin film silicon tandem cell — Andreas Bielawny[1], •Johannes Üpping[1], Paul T. Miclea[1], Ralf B. Wehrspohn[1], Carsten Rockstuhl[2], Falk Lederer[2], Marius Peters[3], Lorenz Steidl[4], Rudolf Zentel[4], Seung-Mo Lee[5], Mato Knez[5], Andreas Lambertz[6], and Reinhard Carius[6] — [1]Institute of Physics, mikroMD, University of Halle Wittenberg — [2]Institue of Physics, Solid States Optics, University of Jena — [3]Freiburg Centre for Material Research, University of Freiburg — [4]Dept. of Chemistry, Pharmacy and Earth Sci-

ence, University of Mainz — [5]Max Planck Institute of Microstructure Physics Halle — [6]Institute of Energy Research, IEF-5 Photovoltaics, Forschungszentrum Jülich GmbH

The concept of 3D photonic intermediate reflectors for micromorph silicon tandem cells has been investigated toward first prototype cells. The reflector enhances the absorption of spectrally selected light in the top cell and decreases the current mismatch between both junctions. Our device is an inverted opal structure made of ZnO and built using self organized nanoparticles and atomic layer deposition coating methods. This 3D photonic crystal intermediate layer is less dependent of the angle of incidence than other state of the art thickness dependent massive interlayers. We present design rules, preparation and characterization of a 3D photonic thin film device. A first prototype is compared to a state of the art reference silicon tandem cell.

HL 5.7 Mon 12:00 POT 151

Silicon nitride passivation of phosphorus highly doped emitters for p-type silicon solar cells — •Kamal Katkhouda[1,2], Karsten Meyer[1], Kevin Lauer[3,2], Roman Petres[4], Sviatoslav Shokhovets[2], and Gerhard Gobsch[2] — [1]ersol Solar Energy AG, Wilhelm-Wolff-Str. 23, 99099 Erfurt, Germany — [2]TU Ilmenau, Institut für Physik, Weimarer Str. 32, 98693 Ilmenau, Germany — [3]CiS Forschungsinstitut für Mikrosensorik und Photovoltaik GmbH, SolarZentrum Erfurt, Konrad-Zuse-Str. 14, 99099 Erfurt, Germany — [4]ISC International Solar Energy Research Centre Konstanz, Rudolf-Diesel-Str. 15, 78467 Konstanz, Germany

Solar cell passivation has always been an attractive topic for photovoltaic researches as this can enhance the performance of the solar cell remarkably. For a solar cell fabricated on p-type silicon it is necessary to achieve a good passivation on a phosphorus highly doped emitter. Silicon dangling bonds saturation and the field effect induced by built-in charge in the passivation-layer are the two well-known passivation effects on silicon surfaces. Some commonly used passivation layers, like SiO2 and SiNx, result in a positive built-in charge while others, e.g. Al2O3, produce a negative charge. Our main focus in this work are SiNx passivation films which were deposited by plasma enhanced chemical vapor deposition (PECVD) technique on different phosphorus highly doped emitter under varying gas flux ratio of silane and ammonia in the PECVD chamber. Optical properties of the films were characterized by spectroscopic ellipsometry while their passivation quality was studied by means of emitter saturation current measurement.

15 min. break

HL 5.8 Mon 12:30 POT 151

Influence of the excess carrier density depth profile on the photoluminescence yield — •Sebastian Knabe and Gottfried H. Bauer — Institute of Physics, University of Oldenburg, Germany

The photoluminescence (PL) emitted from excited semiconductors provides access via Planck's generalizes law to parameters like splitting of quasi-Fermi-levels, optical absorption, temperature and is originated by radiative recombination. The photon flux monitored in the detector is composed of the individual fluxes emitted from each volume element of the sample isotropically into the solid angle 4 π and particularly propagating across the sample to the surface.

We numerically reproduce the spectral PL by a one-dimensional diffusion excess carrier profile for depth dependent emission, including surface recombination velocities, excess carrier lifetimes and diffusion lengths, considering as well optical absorption, reflection at surfaces and according phase accumulation by a matrix transfer approach.

As the splitting of quasi-Fermi-levels usually is deduced experimentally from the high energy wing of the spectral PL-yield we show the limits and quantify the accuracy of this methods versus different excess depth profiles resulting from various surface recombination velocities and from depth dependent carrier lifetimes as well. We furthermore discuss the difference in spectral PL-behavior between a plane wave approach applicable for layer thicknesses being small compared with the laser excitation area and small spot excitation e.g. for SNOM experiments.

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Diffusion of substrate impurities into solar-grade CIGS layer structures — •Shahmahmood Obeidi[1], Roland Würz[2], Axel Eicke[2], and Nicolaas Stolwijk[1] — [1]Institute of Materials Physics, University of Münster, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany — [2]Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg, Industriestr. 6, 70565 Stuttgart, Germany

The deposition of CIGS involves the diffusion of impurities out of the substrate through the Mo back contact into the absorber layer of the solar cell. In some cases, e.g., Fe the performance of the cell is found to suffer. Therefore it is important to study the diffusion behaviour of such impurities both qualitatively and quantitatively. We investigated the diffusion of iron in polycrystalline CIGS after growth. In order to start with Fe-free CIGS layers before the diffusion experiment we chose CIGS/Mo/float-glass structures as samples and provided them with front-side Fe sources. Two methods were applied: the radiotracer method using Fe-59 as suitable isotope and secondary ion mass spectrometry (SIMS) with natural Fe as diffusion source. Diffusion anneals in the temperature range from 200°C to 500°C were performed in a lamp furnace or an oil bath. The values for the diffusion coefficient range from $7.5 \cdot 10^{-15}$ to $8.8 \cdot 10^{-12}$ $cm^2 s^{-1}$ in the temperature interval investigated. An activation enthalpy of 1.0 eV was determined from an Arrhenius fit and the extrapolation of the Arrhenius line to the CIGS deposition temperature (550°C) yields a diffusion coefficient of $2.0 \cdot 10^{-10}$ $cm^2 s^{-1}$. We will discuss to what extent the present results may be interpreted in terms of grain boundary diffusion.

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Carrier collection efficiency in chalcopyrite solar cells with varied absorber layer thickness — •Heiner Lendzian[1], Janet Neerken[1], Martin Knipper[1], Jürgen Parisi[1], Ingo Riedel[1], Stefan Jost[2], Thomas Dalibor[2], and Jörg Palm[2] — [1]Energy- and Semiconductor Research Laboratory, Department of Physics, Carl von Ossietzky University of Oldenburg, D-26111 Oldenburg, Germany — [2]AVANCIS GmbH & Co. KG, Otto-Hahn-Ring 6, Gebäude 31, D-81739 Munich, Germany

In this contribution we examine the effect of thickness-reduced absorber thin films employed in efficient chalcopyrite solar cells on the presence of defect states and photon conversion efficiency as well as the inherent limitation of carrier collection lengths. The investigated solar cells were produced in a well controlled and reliable pilot line and were characterized by means of current-voltage and capacitance-voltage profiling. Furthermore, the spectral absorption coefficient was measured and the resulting absorption depth is compared to the results obtained from spectral response measurements. The analysis yields an accurate determination of effective carrier collection lengths and thereby a good estimate of optimal absorption layer thicknesses.