

## HL 93: Photovoltaics (HL, jointly with CPP, O)

Time: Friday 9:15–13:45

Location: H2

HL 93.1 Fri 9:15 H2

**Simulation of TRPL on thin film solar cells** — ●MATTHIAS MAIBERG, MARIA GAUDIG, and ROLAND SCHEER — Institute of Physics, Martin-Luther-University Halle-Wittenberg, Von-Danckelmann-Platz 3, 06406 Halle, Germany

In the recent years time-resolved photoluminescence (short: TRPL) on semiconductor devices has been established as a non-destructive, non-invasive, contactless characterization method. The decay of the signal has not been fully understood yet. Therefore we studied TRPL on semiconductor layers and thin film solar cells by simulation with Synopsys TCAD. At first we investigated the influence of excitation, diffusion, photon recycling, bulk-defects and defects at the contacts, as well as space charge and potential fluctuations on the PL-decay separately by quasi-one-dimensional simulations of absorber layers and thin film solar cells. We also studied the influence of grain boundaries, since materials like Cu(In,Ga)Se<sub>2</sub> and Cu<sub>2</sub>ZnSnSe<sub>4</sub> are in general polycrystalline. We show, that the samples can be characterized by excitation dependent measurements in the open circuit case. We can explain some effects found in photoluminescence experiments, like a decrease of the lifetime with an increasing excitation, a maximum lifetime due to saturated bulk-defects, and a lifetime of more than 10μs in case of charge separation due to the electric field in the space charge region.

HL 93.2 Fri 9:30 H2

**3D reciprocal space imaging of individual Cu(In,Ga)Se<sub>2</sub> nanocrystallites inside a thin film solar cell** — ●TARAS SLOBODSKYY<sup>1</sup>, ANATOLIY SLOBODSKYY<sup>2</sup>, BORIS LANDGRAFF<sup>1</sup>, CHRISTIAN HEYN<sup>1</sup>, and WOLFGANG HANSEN<sup>1</sup> — <sup>1</sup>Institute for Applied Physics, University of Hamburg, Jungiusstraße 11, D-20355 Hamburg, Germany — <sup>2</sup>Karlsruhe Institute of Technology (KIT), Light Technology Institute (LTI), Kaiserstraße 12, 76131 Karlsruhe, Germany

In this contribution we will present results of an investigation of strain distributions inside of individual Cu(In,Ga)Se<sub>2</sub> nanocrystallites located inside a solar cell absorber layer. The strain is imaged using synchrotron radiation.

We find that the investigated crystallites are non homogeneously strained. The strain is produced by surrounding nanocrystals in the polycrystalline semiconductor film and carries information about the intercrystalline interactions. The measurements are done non destructively and without additional sample preparation or X-ray beam nanofocusing.

The demonstrated technique provides a way for connecting variations in the properties of individual crystallites inside of a working solar cell to the resulting energy conversion efficiency.

HL 93.3 Fri 9:45 H2

**Investigations of chemical gradients in Cu(In,Ga)Se<sub>2</sub> thin film solar cells grown on polyimide substrate by high spatially resolved cathodoluminescence microscopy** — ●STEFAN RIBBE<sup>1,2</sup>, ANDREAS RAHM<sup>1</sup>, FRANK BERTRAM<sup>2</sup>, and JÜRGEN CHRISTEN<sup>2</sup> — <sup>1</sup>Solarion AG, Ostende 5, 04288 Leipzig, Germany — <sup>2</sup>Institute for Experimental Physics, Otto-von-Guericke-Universität Magdeburg, Germany

Optical properties of Cu(In,Ga)S<sub>2</sub>(CIGS)-absorber layers for thin film solar cells have been studied by high spatially resolved cathodoluminescence (CL) at low temperature (T = 5K) to investigate lateral and vertical changes of the composition within the quaternary absorber. CIGS layers were grown on flexible polyimide foil by using an ion-beam assisted roll-to-roll process. To ensure high efficiency sodium fluoride was evaporated by an additional source during the process. The substrate temperature was varied above the standard value enabled by using an advanced polyimide substrate resisting higher temperatures. Cross sections of the thin film solar cells were prepared to investigate the vertical distribution of composition and its changes influenced by the substrate temperature. IV measurements showed an increase of the efficiency with higher substrate temperature suggesting less fluctuation of the composition and a smoother vertical gallium gradient. Furthermore a variation of the sodium content was made by variation of the evaporation temperature. Integral luminescence properties were investigated which showed a red shift and a broadening of the main peak with increased sodium content.

HL 93.4 Fri 10:00 H2

**Admittance spectroscopy on Cu(In,Ga)Se<sub>2</sub> solar cells with respect to sodium content** — ●FELIX DAUME<sup>1,2</sup>, ANDREAS RAHM<sup>1</sup>, and MARIUS GRUNDMANN<sup>2</sup> — <sup>1</sup>Solarion AG, Ostende 5, 04288 Leipzig, Germany — <sup>2</sup>Institut für Experimentelle Physik II, Universität Leipzig, Linnéstraße 5, 04103 Leipzig, Germany

Solar cells based on Cu(In,Ga)Se<sub>2</sub> (CIGSe) absorbers deposited on flexible polyimide substrate enable cheap manufacturing with roll-to-roll equipment and the application in new environments such as low-load rooftops. Among present thin film flexible solar cell technologies, CIGSe achieves the highest efficiencies. The proper incorporation of sodium into the CIGSe absorber is indispensable to achieve these high efficiencies. In this study, sodium fluoride is co-evaporated during CIGSe deposition.

CIGSe solar cells with different sodium contents were investigated by admittance spectroscopy. We calculated activation energies for the N1 signature which, in literature, is widely attributed to defects. Overall concentrations and density profiles across the band gap were derived for this signature. Additionally, we derived the net doping of the CIGSe absorbers from capacitance-voltage measurements. A model based on defects at the CdS(n-type)/CIGSe(p-type) interface is proposed to explain our observations with respect to the sodium content.

HL 93.5 Fri 10:15 H2

**High-resolution Spectroscopic Mapping of Polymer Fullerene Blend Films for Organic Solar-Cell Applications** — XIAO WANG, KAI BRAUN, ALFRED J. MEIXNER, and ●DAI ZHANG — Institute of Physical and Theoretical Chemistry, Uni. Tübingen, Tübingen

Polymers and fullerenes are widely employed in the field of organic solar cells as the electronic donors and acceptors. The morphology and the photo-physical properties of the polymer and fullerene blends at nanometer scale are critical for achieving a high performance of the solar cells. Employing a home-built parabolic mirror assisted apertureless near-field optical (Raman and photoluminescence) microscope, we demonstrated high resolution near-field spectroscopic mappings of the polymer:fullerene blend films. Our investigation focused on the additive effect for a C-PCPDTBT:PCBM blend film. From the simultaneously recorded morphology and spectroscopic information, the interplay among the blend film morphology, the local donor and acceptor molecular distributions, and the photoluminescence quenching efficiency were discussed. The PL and Raman signals of the electron donor and acceptor have been probed at an optical resolution of approximately 10 nm which allow the direct identification of the chemical nature of the different domains. Moreover, we were able to reveal and quantify the local quenching, which is related to the electron transfer from donor to acceptor.

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**Investigation of the s-shape caused by the hole selective layer in organic bulk heterojunction solar cells** — ●LOTHAR SIMS<sup>1,2</sup>, ULRICH HÖRMANN<sup>2</sup>, RENÉ KOGLER<sup>3</sup>, ROLAND STEIM<sup>4</sup>, WOLFGANG BRÜTTING<sup>2</sup>, and PAVEL SCHILINSKY<sup>1</sup> — <sup>1</sup>Belectric OPV GmbH, Landgrabenstr. 94, 90443 Nürnberg — <sup>2</sup>University of Augsburg, Institute of Physics, Universitätsstr. 1, 86135 Augsburg — <sup>3</sup>Evonik Industries AG, Kirschenallee, 64293 Darmstadt — <sup>4</sup>STORM Energy GmbH, Rathenauplatz 2, 90489 Nürnberg

During the operation period of an organic solar cell different failure mechanisms can occur which limit the lifetime of the device. Among these failure mechanisms the so called s-shape or second diode, where the current density-voltage (JV) curve bends towards the origin in the 4th quadrant, plays an important role. We investigated the origin of the s-shape caused by the hole selective layer (HSL) using N,N'-bis(3-methylphenyl)-N,N'-bis(phenyl)-benzidine (TPD) coevaporated with different amounts of Dipyrazino[2,3-f:2',3'-h]quinoxaline-2,3,6,7,10,11-hexacarbonitrile (HATCN) as a model system. The low glass transition temperature of TPD allows investigating the impact of WF and mobility of the HSL on device performance and thus s-shape independently of each other. The observed JV-curves were simulated by solving the drift-diffusion, i.e. continuity and Poisson equations numerical via the program PC1D. While WF rather influences the open circuit voltage, mobility seems to be the reason for the s-shape. The results show that an accumulation of holes near the hole selective/semiconductor layer

interface might be responsible for the observed s-shape.

HL 93.7 Fri 10:45 H2

**The role of defects in nanocrystalline zinc oxide interlayers for polymer-based solar cells** — ●SEBASTIAN WILKEN, DOROTHEA SCHEUNEMANN, FLORIAN WITT, JÜRGEN PARISI, and HOLGER BORCHERT — University of Oldenburg, Department of Physics, Energy and Semiconductor Research Laboratory, Carl-von-Ossietzky-Str. 9-11, 26129 Oldenburg, Germany

In polymer-based bulk heterojunction solar cells, the absorber blend has intrinsically no preferential transport direction for photogenerated charge carriers due to the statistical intermixing of both the donor and acceptor phase. Therefore, additional charge-selective interfacial layers, which are semipermeable membranes for either electrons or holes in an ideal case, are widely used in order to achieve efficient charge extraction at the respective contacts. One well established material for electron collection is zinc oxide (ZnO), which can be processed at moderate temperatures and deposited via solution-based techniques in form of colloidal nanocrystals (NCs). Here, we discuss the influence of defect states in interlayers made of ZnO NCs on the overall solar cell performance. For that purpose, ZnO NCs with different surface-to-volume ratios were wet-chemically synthesized and introduced into indium tin oxide-free polymer solar cells in the inverted device architecture. As indicated by photoluminescence, we show that surface defects play a more and more dominant role with decreasing NC size and, thus, limit the photovoltaic efficiency. For a more detailed analysis of the involved defect states, photo-induced current transient spectroscopy (PICTS) was performed for devices with varying amount of surface defects.

HL 93.8 Fri 11:00 H2

**Solar diode sensor** — ●HAO SHEN<sup>1</sup>, MARTIN HOFFMANN<sup>1</sup>, JUAN DANIEL PRADES<sup>2</sup>, FRANCISCO HERNANDEZ-RAMIREZ<sup>3</sup>, and ANDREAS WAAG<sup>1</sup> — <sup>1</sup>Institute of Semiconductor Technology, TU Braunschweig, D-38105 Braunschweig, Germany — <sup>2</sup>Department of Electronics, Uni. Barcelona, E-08028 Barcelona, Spain — <sup>3</sup>Catalonia Institute for Energy Research (IREC), E-08930 Barcelona, Spain

The nanodevice architecture presented here has been designed to overcome the current issues in gas sensor technologies: reducing power consumption and lowering operating temperature. Conductometric sensors based on semiconductor metal oxides need the continuous supply of the energy in the form of heat or UV light, to activate the chemical interaction between gases and the sensing surface. New concepts for energy harvesting units as an in-built module are demanded to make self-powered gas sensors. Herein we report a solar diode sensor (SDS) based on new designed CdS@n-ZnO/p-Si nanoelements which unifies gas sensing (CdS@n-ZnO) and solar energy harvesting (n-ZnO/p-Si diode) functionalities in a singular material unit and device. The SDS sensing mechanism (change of open circuit voltage), in comparison to the well-known conductometric sensors (change of resistance), is systematically studied and explained in terms of gas-material surface interactions and the subsequent changes in the doping level (ND), which is manifested in the variation of Voc in CdS@n-ZnO/p-Si. The fabricated SDS was capable of quantitatively detecting oxidising and reducing gases with reproducible response at room temperature and without the need of any other energy sources except solar illumination.

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**Simulation of temperature distribution in ZnO:Al thin films for laser annealing experiments** — ●CHRISTIAN ISENBERG, CAY-CHRISTIAN KALMBACH, DANIYAL SATTARIAN, UWE STUTE, and ALEXANDER HORN — Laser Zentrum Hannover e.V., Hollerithallee 8, 30419 Hannover, Germany

Transparent Conducting Oxides (TCOs) have become widespread as transparent electrodes in photovoltaics and transparent electronics. Thermal post deposition treatments by furnace annealing have shown to improve the electrical and optical properties of TCO thin films. Laser annealing of TCOs allows control over the peak temperature as well as the spatial and temporal temperature distributions of TCO thin films and substrates, preserving the substrate by heating only the TCO layer. Therefore, treating TCOs with tailored laser radiation allows larger temperature than furnace annealing even on temperature sensitive substrates. Numerical calculations using Crank-Nicolson method have been conducted to estimate the temperature distribution in ZnO:Al thin films during laser annealing process. In the special case of temperature-independent material parameters, the numerical solution is reduced to an analytical solution, determined by convolution

of the heating source term with a Green's function for a geometry of a thin film on a semi-infinite substrate. Numerical results are compared to temperature measurements, done by a thermographic camera during laser annealing process.

Coffee break

HL 93.10 Fri 11:45 H2

**Selective laser ablation of Al<sub>2</sub>O<sub>3</sub> passivation layers from optically black silicon surfaces** — ●MARTIN OTTO<sup>1</sup>, KATHARINA WIDDER<sup>1</sup>, TINO RUBLACK<sup>1</sup>, MATTHIAS ZILK<sup>2</sup>, THOMAS KÄSEBIER<sup>2</sup>, GERHARD SEIFERT<sup>1</sup>, and RALF B. WEHRSPHORN<sup>3</sup> — <sup>1</sup>Martin-Luther-University Halle-Wittenberg, Institute of Physics -μ MD Group, Heinrich-Damerow-Strasse 4, 06120 Halle, Germany — <sup>2</sup>Friedrich Schiller University Jena, Institute of Applied Physics, Max-Wien-Platz 1, 07743 Jena, Germany — <sup>3</sup>Fraunhofer Institute for Mechanics of Materials Halle, Walter-Hülse-Str. 1, 06120 Halle, Germany

Inductive coupled plasma reactive ion etching (ICP-RIE) of silicon enables excellent broad band and wide angle antireflective surface properties. The stochastically emerging needle like nano-structures let the silicon surface appear optically black due to its high absorption coefficient of over 97% integrated from 300 nm to 1175 nm. Concomitant, highly enhanced surface recombination is introduced. The latter, may be effectively suppressed by a well suited passivation layer of Al<sub>2</sub>O<sub>3</sub> deposited by thermal ALD. Laser ablation is commonly used in the PV industry to open local contact areas in dielectric passivation stacks. In this work we show the feasibility to ablate alumina thin films from nano-structured black silicon (b-Si) solar cell front surfaces. Microstructural geometric analysis by focussed ion beam and SEM reveal certain structural changes in the zone of ablation which are believed to be beneficial for contact formation. Simultaneously, neither the deposition of Al<sub>2</sub>O<sub>3</sub> layers of varying thickness nor their ablation lead to a very significant degradation of the optical surface properties.

HL 93.11 Fri 12:00 H2

**Surface Modification of Nano-Textured Black Silicon for Photovoltaic Applications** — ●MICHAEL ALGASINGER<sup>1</sup>, SVETOSLAV KOYNOV<sup>1</sup>, JULIE PAYE<sup>1</sup>, FLORIAN WERNER<sup>2</sup>, MAX BERNT<sup>1</sup>, MARTIN S. BRANDT<sup>1</sup>, and MARTIN STUTZMANN<sup>1</sup> — <sup>1</sup>Walter Schottky Institut, Technische Universität München, 85748 Garching, Germany — <sup>2</sup>Institute for Solar Energy Research Hamelin, Am Ohrberg 1, 31860 Emmerthal, Germany

The morphology and the electronic properties of nano-textured silicon, obtained by a metal-catalyzed wet etching process and its improvement by an additional chemical treatment are examined with regard to solar cell applications. Photoluminescence and optical reflectivity measurements show evidence for a nano-porous silicon (np-Si) phase in the as-prepared nanostructure. It is found that an additional wet-chemical treatment removes the np-Si fraction and significantly alters the surface of the nanostructure. Cross-sectional scanning electron microscopy images reveal a drastic reduction of the surface area, to values of only 3 - 6 times of that of a planar surface. Electron spin resonance measurements were performed to investigate the type and quantity of defects induced by the nano-texturing process. First results on the passivation of surface defects via atomic layer deposition of Al<sub>2</sub>O<sub>3</sub> are presented. Photoconductance decay measurements of passivated nanostructures, which received the additional post-etching treatment, show a significant increase in effective carrier lifetimes.

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**Surface morphology of black silicon produced by metal-catalyzed wet etching** — ●MAXIMILIAN BERNT, MICHAEL ALGASINGER, SVETOSLAV KOYNOV, and MARTIN STUTZMANN — Walter Schottky Institut, Technische Universität München, 85748 Garching, Germany

Nano-textured silicon, also referred to as black silicon (b-Si), is a material with an optically graded surface, which shows reflectivity as low as 1 - 5 % in the whole range of Si absorption and additional light trapping effects. Due to its unique optical properties, b-Si is an interesting material for photovoltaic applications. However, b-Si produced by Au-catalyzed wet etching of crystalline Si (c-Si) wafers exhibits a nano-porous silicon (np-Si) phase in the as-prepared nano-structure. This np-Si phase leads to an increased surface area which could alter the electrical properties significantly. The formation of the nano-texture was investigated at different stages of the etch process by cross sectional scanning electron microscopy. The evolution of the np-Si

phase with increasing etch time was observed by photoluminescence and optical reflectivity measurements. In addition, the influence of the doping level of n- and p-type c-Si substrates on the etch process and the morphology of the resulting nano-texture was studied.

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**Valence band offsets estimation of Al<sub>2</sub>O<sub>3</sub> films on silicon by XPS and UPS measurements** — ●JOHANNES ZIEGLER<sup>1</sup>, VOLKER NAUMANN<sup>2</sup>, MARTIN OTTO<sup>1</sup>, ALEXANDER SPRAFKE<sup>1</sup>, and RALF B. WEHRSPORN<sup>1,3</sup> — <sup>1</sup>Martin-Luther-University Halle-Wittenberg, Institute of Physics, Halle, Germany — <sup>2</sup>Fraunhofer Center for Silicon Photovoltaics CSP,Halle, Germany — <sup>3</sup>Fraunhofer Institute for Mechanics of Materials Halle, Halle, Germany

A quantitative measurement of valence band offsets in isolator-silicon junctions might help to realize heterojunction devices such like semiconductor-isolator-semiconductor (SIS) solar cells. We measured XPS and UPS spectra of thin (2–50 nm thick) Al<sub>2</sub>O<sub>3</sub> films deposited on silicon by thermal ALD. The valence band offsets of these structures are estimated from the XPS spectra using the method of Kraut et.al. [1]. A slight trend in the valence band offsets 3.3–4.5 eV with increasing film thickness 2–50 nm was calculated from the XPS spectra. To estimate the valence band offsets from the UPS spectra 3.3–3.4 eV of 2–10 nm thick Al<sub>2</sub>O<sub>3</sub> on silicon, a simple straight forward approach based on linear regression of the spectra on the band edges is used. We compare the results of both measurements and discuss possible sources for the measured increase of the valence band offset with increasing Al<sub>2</sub>O<sub>3</sub> film thickness.

[1] A. Kraut, R. W. Grant, J. R. Waldrop and S. P. Kowalczyk, Phys. Rev. Lett. 44,p.1620 (1982), <http://link.aps.org/doi/10.1103/PhysRevLett.44.1620>

HL 93.14 Fri 12:45 H2

**Charge trapping in Al<sub>2</sub>O<sub>3</sub> passivation layers for silicon solar cells** — ●PAUL JORDAN<sup>1</sup>, FRANK BENNER<sup>1</sup>, INGO DIRNSTORFER<sup>1</sup>, and THOMAS MIKOLAJICK<sup>1,2</sup> — <sup>1</sup>NaMLab gGmbH, Dresden, Germany — <sup>2</sup>Lehrstuhl für Nanoelektronische Materialien, TU Dresden, Dresden, Germany

Novel highly efficient silicon solar cells require an excellent level of surface passivation, to minimize recombination losses of photo-generated carriers. During the last decade, the dielectric Al<sub>2</sub>O<sub>3</sub> became the material of choice for the passivation of p-type silicon. The excellent passivation properties are mainly caused by negative charges located within the dielectric. In this study the origin of the negative charges is investigated using capacitance-voltage and microwave detected photo-conductivity measurements. It will be shown that the negative charges are partly caused by electrons, injected from silicon into the dielectric. The trapping dynamics are analyzed by the means of the post program discharge technique, which is commonly applied for memory devices. Furthermore, the trapping and detrapping rates depend on the thickness of the ultra-thin SiO<sub>2</sub> interface between Si and Al<sub>2</sub>O<sub>3</sub>. For an interface thickness of about 2 nm, the asymmetry of trapping and detrapping rates significantly enhances the negative charge density. As a consequence an optimum interface thickness is essential for the excellent passivation property of Al<sub>2</sub>O<sub>3</sub>.

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**Investigation of carrier traps in pn-junctions of fully-processed silicon photovoltaic cells** — ●TEIMURAZ MCHEDLIDZE, LEOPOLD SCHEFFLER, and JÖRG WEBER — Technische Universität Dresden, 01062 Dresden, Germany

Mesa-diodes with a surface area about 1 mm<sup>2</sup> and a height of 50 μm were fabricated on top of fully-processed Si photovoltaic-cell wafers for detection and investigation of carrier traps in pn-junctions. All fabrication steps were performed at room temperature and fully preserved the initial structure of the cell inside the mesa-diode. Schottky diodes were fabricated on neighbor locations of the wafers after etching off the PV-cell structure to a depth of 50 μm. The DLTS spectra detected for the mesa- and Schottky-diodes show significant difference, namely the deep carrier traps detected in the mesa-structures were below the detection limit in the Schottky-diodes. Profiling of the trap density for the mesa-diodes showed a steep decrease with increasing distance from the pn-junction. Parameters of the detected traps, their possible origin and reasons for the differences between spectra detected for mesa- and Schottky-diodes are presented and discussed.

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**Iron acceptor association in compensated multicrystalline silicon** — ●CHRISTIAN MÖLLER<sup>1,2</sup>, KEVIN LAUER<sup>1</sup>, FABIEN GIBAJA<sup>3</sup>, TIL BARTEL<sup>3</sup>, and FRITZ KIRSCHT<sup>3</sup> — <sup>1</sup>CiS Forschungsinstitut für Mikrosensorik und Photovoltaik GmbH, SolarZentrum Erfurt, Konrad-Zuse-Str. 14, 99099 Erfurt, Germany — <sup>2</sup>TU Ilmenau, Institut für Physik, Weimarer Str. 32, 98693 Ilmenau, Germany — <sup>3</sup>Calisolar GmbH, Magnusstraße 11, 12489 Berlin

Monitoring the acceptor concentration in compensated multicrystalline silicon by a minority-charge carrier lifetime measurement is applicable for production control due to the fast and easy lifetime measurement. The iron acceptor pair association is studied for several acceptors position dependent over the whole height of a compensated multicrystalline ingot. Acceptor pair and height dependent induced differences in the defect kinetics are visible. The calculated position depending doping concentrations of several ingots from charge carrier lifetime measurements are discussed and compared with the expected doping concentration calculated via Scheil equation.

HL 93.17 Fri 13:30 H2

**Femtosecond laser processed sulfur-emitter solar cells** — ●THOMAS GIMPEL<sup>1</sup>, KAY-MICHAEL GÜNTHER<sup>2</sup>, ANNA LENA BAUMANN<sup>1</sup>, WOLFGANG SCHADE<sup>1</sup>, and STEFAN KONTERMANN<sup>1</sup> — <sup>1</sup>Fraunhofer Heinrich Hertz Insitute, EnergieCampus, Am Stollen 19B, 38640 Goslar, Germany — <sup>2</sup>Energieforschungszentrum Niedersachsen, EnergieCampus, Am Stollen 19B, 38640 Goslar, Germany

A simple fs-laser process enables structuring and sulfur incorporation simultaneously. This process is applied on a single side to different silicon substrates independent from the crystal structure. Without any advanced solar engineer processes like passivation, dopant source layer deposition, its diffusion and removal, efficiencies of 8.2% are achieved, at present. Due to an incorporated intermediate band this material has the potential to convert infrared light even at wavelengths below the silicon band gap. New applications e.g. in a crystalline silicon tandem solar cell are under development.