Institut für Physikalische Elektronik

Institute of Physical Electronics

Universität Stuttgart

Jahresbericht

Annual Report 2005

Jahresbericht
Annual Report

2005

Redaktion • edited by:

Lydia Gräter
Uwe Rau
Jürgen H. Werner

Vorwort

Liebe Freunde des *ipe*,

in diesem Jahr haben wir (mindestens) zwei Weltrekorde für Solarzellenwirkungsgrade erzielt. Unser neuer Rückseitenprozess für kristallines Silizium mit Hilfe von amorphem Silizium (Leitung: Uwe Rau) lieferte 21 % Umwandlungswirkungsgrad, unser neuer Prozess des Laserdotierens (Leitung: Jürgen Köhler) steht inzwischen bei 17 %. Beide Prozesse sind hoch interessant für die Industrie. Im Jahr 2006 sollte es uns gelingen, hoch-effiziente Silizium-Solarzellen bei Raumtemperatur herzustellen.

Den größten Schritt haben wir allerdings bei unserer kurz vor dem „Aus“ stehenden CIGS-Technologie gemacht. Philip Jackson berichtet hier noch über 19 % als neuer Höchstwert, bei Redaktionsschluss steht die Zahl auf 19,3 % - nur noch 0,2 % unterhalb des Weltrekords für Dünnschichtsolarzellen. In wenigen Monaten haben wir unseren eigenen Europarekord um fast 2 % überboten. Die neu organisierte, sehr kleine Gruppe um Philip Jackson hat Großartiges geleistet.

Das Jahr 2005 war sehr erfolgreich. Ich bin mir sicher, dass wir auch weiterhin erfolgreich agieren werden. Die Stärke des *ipe* ist, dass seine Mitarbeiter in der Lage sind, flexibel in einem sich rasch ändernden Umfeld zu handeln. Dafür danke ich der „Piratentruppe“ des *ipe*.

Stuttgart, Dezember 2005

J. Werner

Jürgen H. Werner

Preface

Dear friends of *ipe*,

This year we have set (at least) two world records for the power efficiency of solar cells. Our new back side process for crystalline silicon with amorphous silicon (leader: Uwe Rau) brought us 21 % conversion efficiency and our new laser doping process (leader: Jürgen Köhler) ranges now at about 17 %. Both processes are most interesting for industry. In the year 2006 we trust that we will succeed in producing high-efficiency silicon solar cells at room temperature.

The biggest step has certainly been made in our CIGS technology, a research field which will soon be shut down at *ipe*. Philip Jackson reports here on 19 % - actually 19.3 % when this report went to press - only 0.2 % below the world record for thin film solar cells. Within a couple of months we have beaten our own European record by almost 2 %! This new organized and very small group working around Philip Jackson has really achieved great things!

The year 2005 was very successful. I am sure that we will continue our effective work. The strength of *ipe* is the talent of its people to act in a flexible way in fast changing surroundings. I would like to thank the "pirate group" of *ipe* for being so.

Stuttgart, December 2005

J. Werner

Jürgen H. Werner


Institut für Physikalische Elektronik

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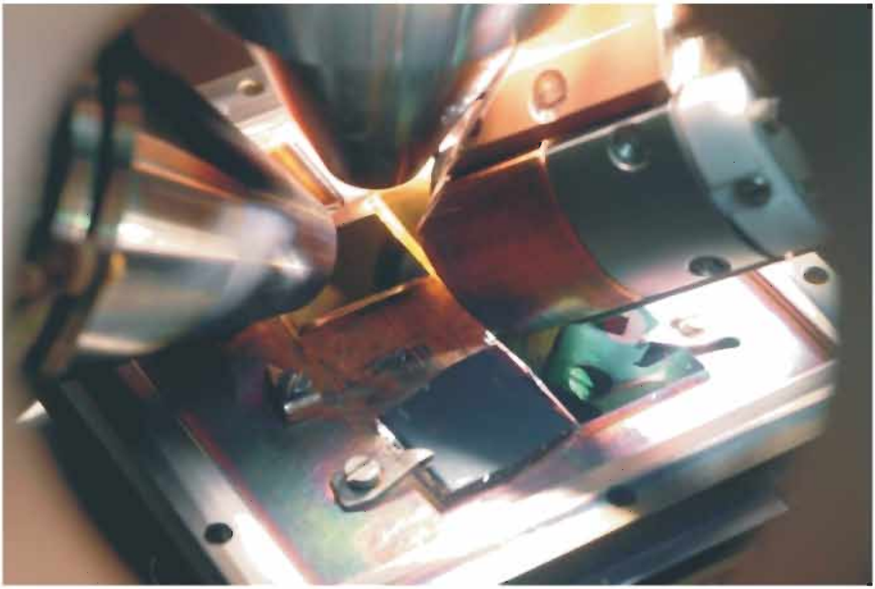


Dünnschichttechnik

Solarzellen

Mikro - und Optoelektronik

Weltrekord

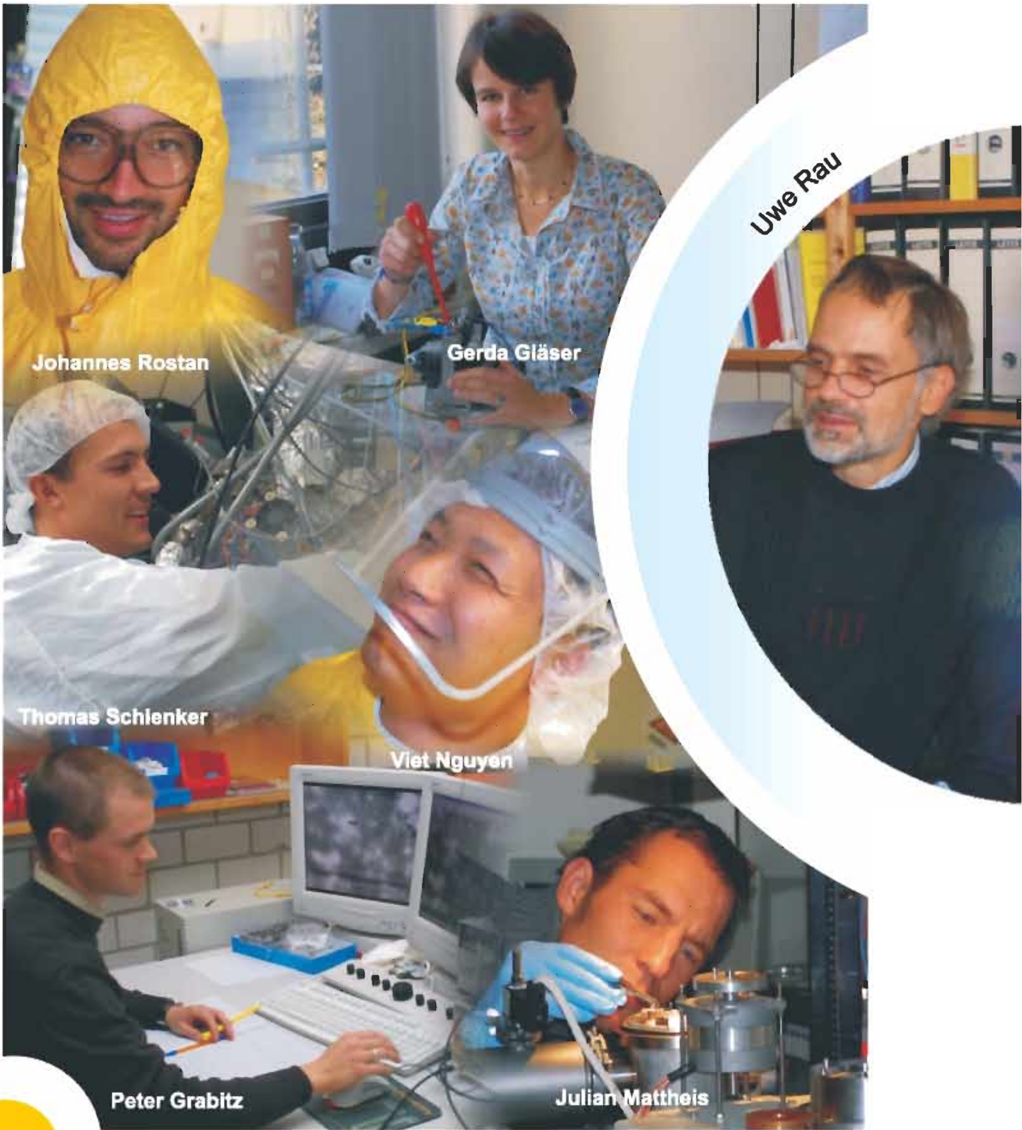
Institutsleitung • Head of the Institute

Verwaltung • Administration

Werkstatt • Workshop

Gruppe Bauelementanalyse
Group Device Analysis

(Gruppenleiter / Group Leader: Uwe Rau)

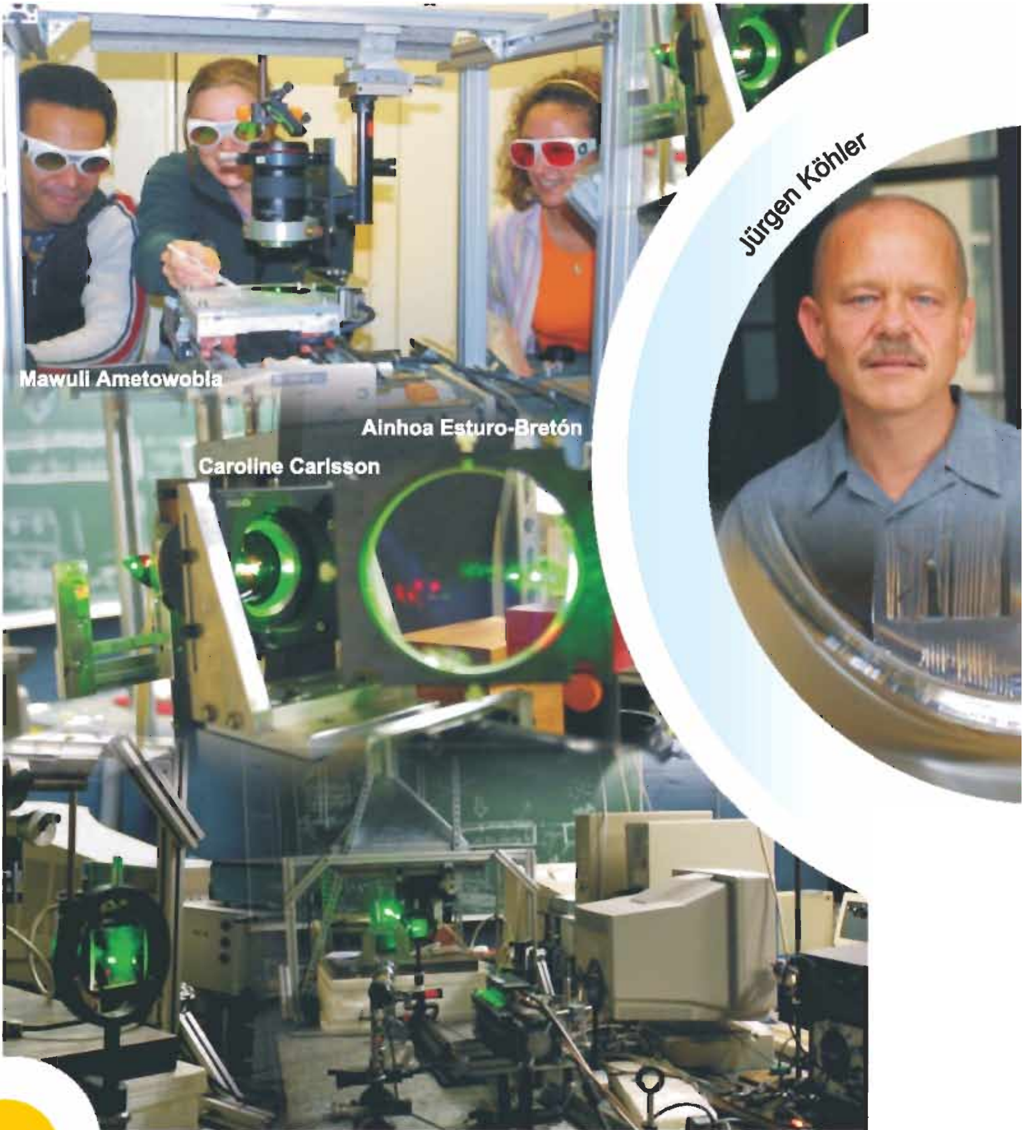


Die Gruppe „Bauelementanalyse" befasst sich mit der elektrischen und optischen Charakterisierung sowie der numerischen Simulation von Solarzellen basierend auf $CdS/Cu(In,Ga)Se_2$ und a-Si:H/c-Si Heterostrukturen, sowie von Farbstoff-Solarzellen auf der Basis von nano-porösem TiO_2. Ziel unserer Aktivitäten ist ein grundlegendes Verständnis der Funktionsweise dieser Bauelemente, des Einflusses der Präparationsbedingungen und des Designs des Baulements auf seine Leistungsfähigkeit. Wir benutzen elektrische Analysemethoden wie Strom-Spannungsmessungen, Admittanzspektroskopie und Transienten-Spektroskopie tiefer Störstellen (DLTS). Messungen der internen Quantenausbeute und Photolumineszenz dienen zur Untersuchung der elektro-optischen Eigenschaften der Materialien. Die experimentellen Resultate werden mit quantitativen, numerischen wie analytischen, Modellen verglichen, um ein kohärentes Verständnis der Bauelemente zu erhalten.

The "device analysis" group investigates the electrical and optical properties of solar cells based on $CdS/Cu(In,Ga)Se_2$ and a-Si:H/c-Si heterojunctions as well as dye-sensitized solar cells based on nano-porous TiO_2. We focus on a fundamental understanding of the working principle of these devices, the influence of preparation conditions and device design on the performance and, finally, on the improvement and optimization. Electrical analysis is performed with the help of current-voltage measurements, admittance spectroscopy, deep level transient spectroscopy (DLTS), and similar methods. Electro-optical analysis comprises measurements of internal quantum efficiency, optical transmittance and reflectance, photoluminescence, etc. The quantitative and coherent interpretation of these experimental results requires detailed modeling and simulation.

Gruppe Laserprozesse
Group Laser Processing

(Gruppenleiter / Group Leader: Jürgen Köhler)



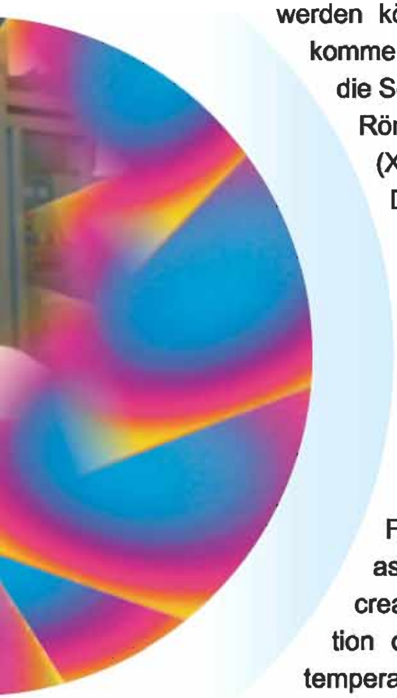
Die Gruppe „Laserprozesse" entwickelt neue Technologien zur Laserprozessierung der am *ipe* verwendeten einkristallinen und polykristallinen Halbleiter. Hierzu zählen die Strukturierung der Halbleiter, deren Kristallisation und Rekristallisation sowie die Laser-Dotierung zur Herstellung von Emittern und Rückseitenkontakten für Silizium-Solarzellen. Im Vordergrund unserer Arbeiten stehen Grundlagenuntersuchungen zur Laserdotierung von kristallinem Silizium. Entwicklungsziele sind die Erhöhung des Durchsatzes bei der laserunterstützten Emitterdotierung sowie die Steigerung der Wirkungsgrade von 100 mm x 100 mm großen Solarzellen auf über 17 %.

The "laser processing" group explores new technologies for laser processing of monocrystalline and polycrystalline semiconductors. Examples are laser structuring, laser annealing, laser crystallization and laser doping crystalline silicon. The main topic of our research work is the investigation of the fundamental processes involved in a pulsed laser doping process for the preparation of phosphorus-doped emitters on crystalline silicon wafers. Development goals are the increase of the throughput rate of the laser doping process as well as the increase of the efficiency of 100 mm x 100 mm sized monocrystalline silicon solar cells to more than 17 %.

Gruppe Neue Materialien
Group New Materials

(Gruppenleiter / Group Leader: Gerhard Bilger)

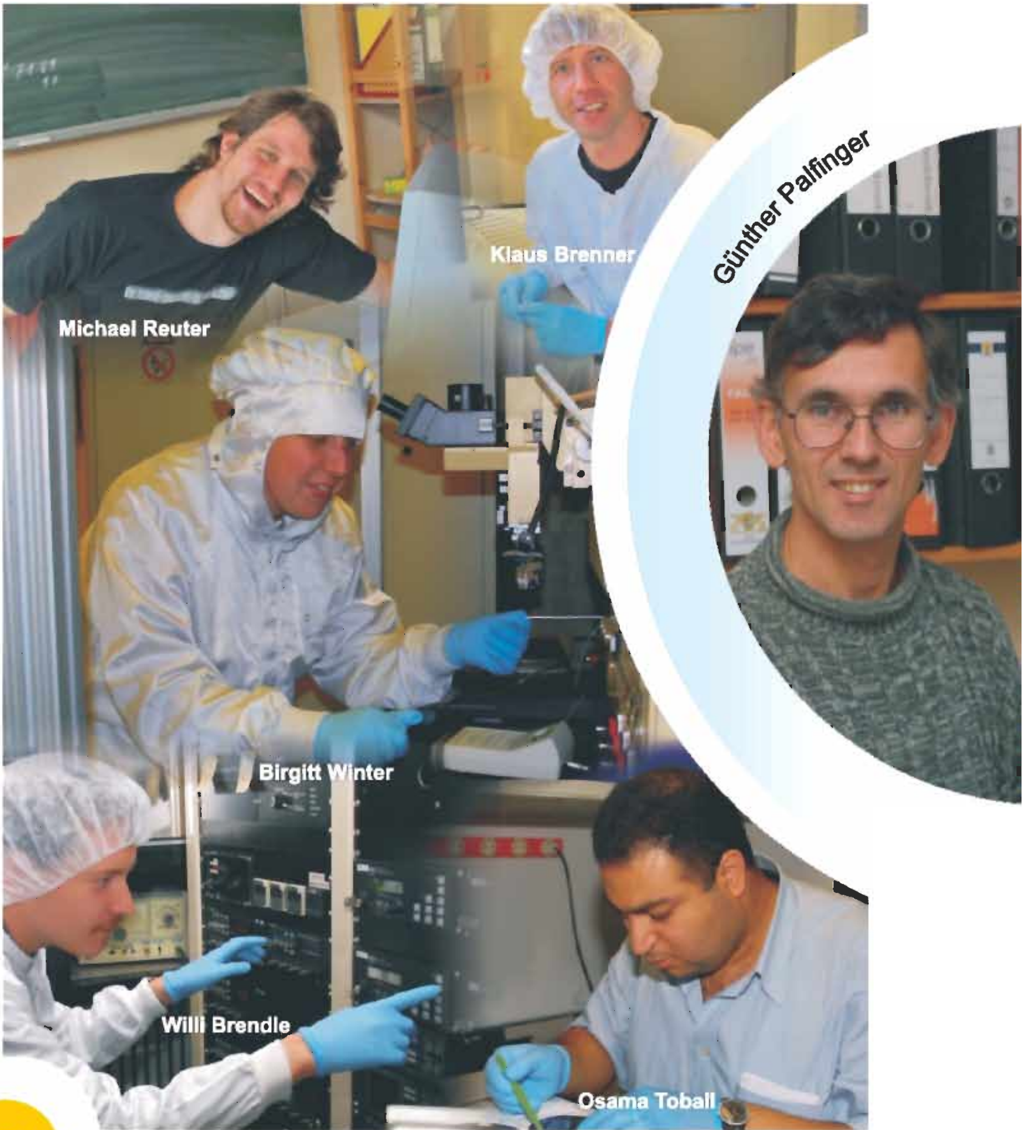
Für die Entwicklung von Solarzellen leisten neuartige Materialien als passive Beschichtung einen wichtigen Beitrag zur Erzielung gesteigerter Quantenausbeuten mit höchsten Wirkungsgraden. Zudem stellen sie bei der Optimierung von Dotierverfahren für Si-Solarzellen durch Niedertemperatur-Laserprozesse speziell angepasste Prekursoren zur Verfügung. Bei dem hier angewandten Verfahren der Hochfrequenz-Zerstäubung (HF-Sputtern) lassen sich praktisch alle Zusammensetzungen als dünne Schichten herstellen, wobei auch reaktive Gase in weiten Bereichen zugemischt werden können. Für die Charakterisierung dieser Schichten kommen Oberflächen- und Dünnschichtanalysemethoden wie die Sekundärionen-Massenspektrometrie (SIMS) sowie die Röntgen- und Ultraviolett-Photoelektronen-Spektrometrie (XPS, UPS) als unabdingbarer Bestandteil zum Einsatz. Die Oberflächenanalytik unterstützt auch alle anderen Forschungs- und Entwicklungsgruppen am *ipe* und wird auch als Dienstleistung für andere Institute und die Industrie angeboten.



For the development of solar cells, novel materials used as passive coating will contribute significantly to an increased quantum efficiency. Furthermore, the optimization of doping procedures for Si solar cells with low-temperature laser processes requires specifically developed precursors. These materials are processed as thin films by means of high frequency sputtering techniques, which admit the preparation of nearly all elemental compositions including reactive gases within wide ranges. For the characterization of these thin films, secondary ion mass spectrometry (SIMS) as well as X-ray and ultraviolet photoelectron spectrometry (XPS, UPS) are used as indispensable analysis methods. The analysis also substantially supports all research and development groups at the *ipe* and is also offered to other institutes and to industry.

Gruppe Photovoltaik
Group Photovoltaics

(Gruppenleiter / Group Leader: Günther Palfinger)

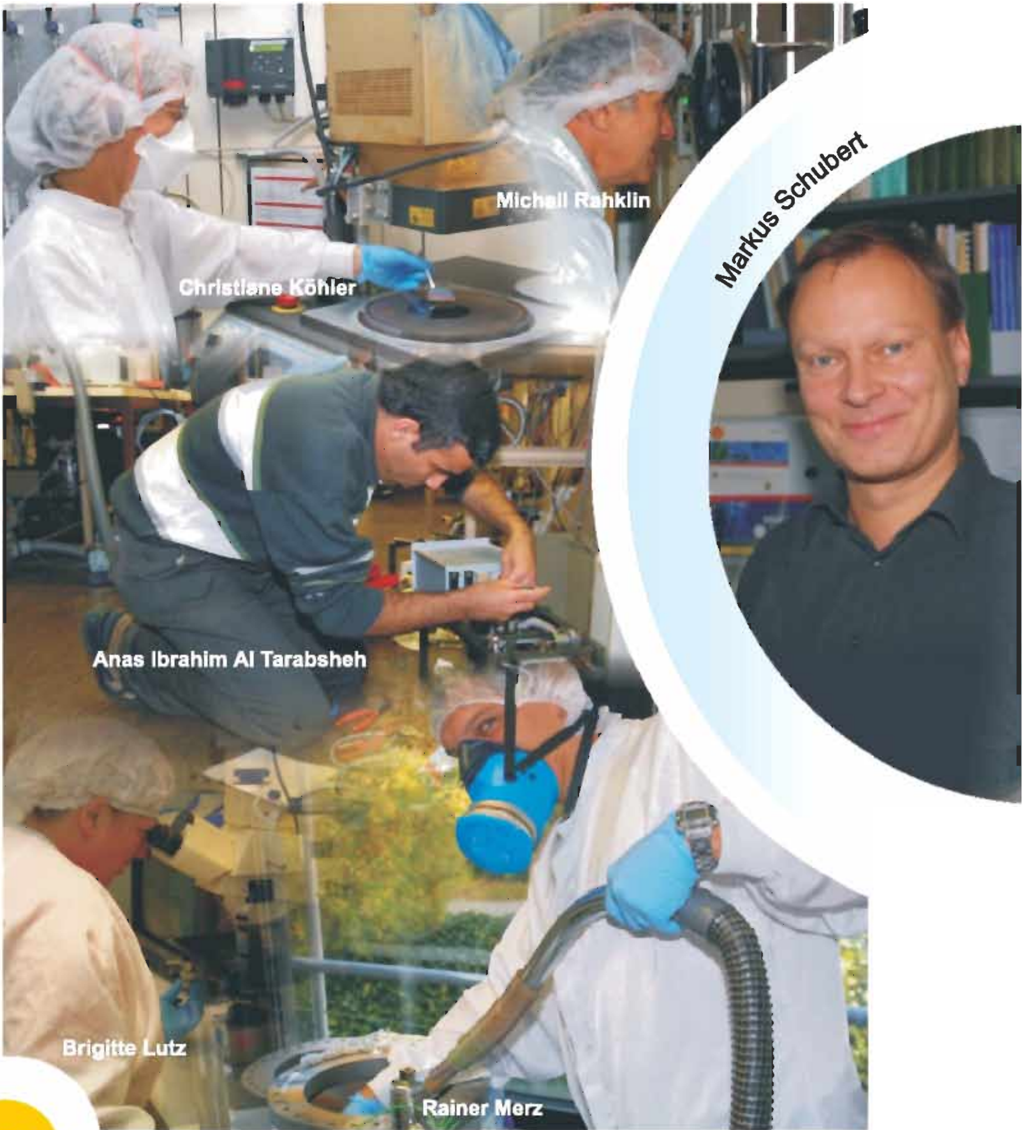


Der Schwerpunkt der Arbeitsgruppe „Photovoltaik" ist die Entwicklung von dünnen monokristallinen Silizium-Solarzellen und der darauf basierenden Module. Der wesentliche Vorteil dieser 20 bis 50 µm dicken Solarzellen ist die Einsparung von Silizium-Rohmaterial, das bei herkömmlichen, 200 bis 300 µm dicken, Silizium-Solarzellen etwa zwei Drittel des Produktionskosten ausmacht. Ein weiterer Vorteil ist die mechanische Flexibilität. Ihr wesentlich höherer Wirkungsgrad im Vergleich zu bisher am Markt verfügbaren flexiblen Solarzellen ermöglicht neue Anwendungen, wie z. B. die Integration in Kleidung. Für die Herstellung der dünnen Siliziumschicht ätzen wir Poren in eine Siliziumscheibe, auf die wir in Kooperation mit *ims-chips* eine 20 bis 50 µm dicke Silizium-Schicht epitaktisch abscheiden.

The "Photovoltaics" group develops thin mono-crystalline silicon solar cells and modules based on them. The advantage of these 20 to 50 µm thick solar cells lies in the reduction of the use of silicon material, which amounts to two thirds of the cost of conventional 200 to 300 µm thick solar cells. Furthermore, thin cells are mechanically flexible. Their higher efficiency in comparison with other flexible cells on the market opens up new applications, e. g. their integration into clothing. The thin silicon layers are manufactured by etching pores into a silicon host wafer, on which in cooperation with *ims-chips* a 20 to 50 µm thick silicon layer is epitaxially deposited. When reusing the host wafer for the next process, only a few µm of the host wafer is actually used up.

Gruppe Sensorik
Group Sensors

(Gruppenleiter / Group Leader: Markus Schubert)

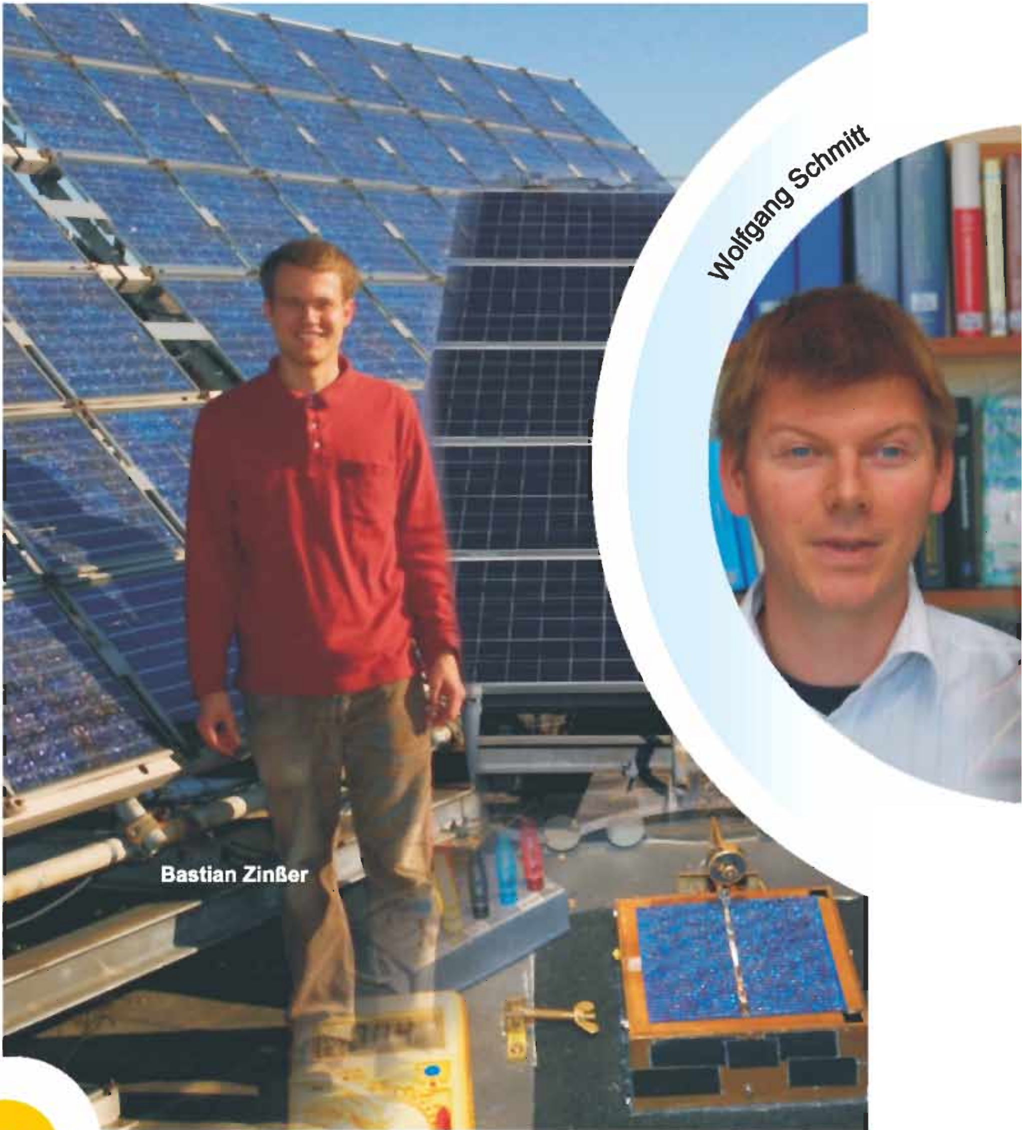


Das technologische Standbein der Arbeitsgruppe „Sensorik" am *ipe* ist die Herstellung amorpher und nanokristalliner Dünnschichthalbleiter auf der Basis von Silizium. Neben reinen Dünnschichtbauelementen aus amorphem Silizium (*a*-Si:H) optimieren wir in Kooperationen innerhalb und außerhalb des *ipe* die Kombination von *a*-Si:H mit wafer-basierten Solarzellen und Mikroelektronik-Schaltungen, zum Beispiel bei der Niedertemperatur-Passivierung von Solarzellen oder bei der Entwicklung von "Thin-Film-on-CMOS"-Kameras, die in enger Kooperation mit dem Institut für Mikroelektronik Stuttgart (*ims-chips*) erfolgt. Bei 100 °C stellen wir flexible Solarzellen und -module aus *a*-Si:H direkt auf Plastikfolie her, welche dann, beispielsweise in Kleidung integriert, mobile elektrische Energie zum Betrieb elektronischer Kleingeräte bereit stellen (*integrierte Photovoltaik - ipv*).

The most important technology of the "Sensors" work group at *ipe* is the deposition of silicon based, amorphous and nanocrystalline thin film semiconductors. In addition to complete thin film devices made of amorphous silicon (*a*-Si:H), we also optimize the combination of *a*-Si:H with wafer-based solar cells and microelectronic circuits in fruitful cooperations inside and outside *ipe*. Successful examples are the low-temperature passivation of monocrystalline Si solar cells, or the development of "Thin-Film-on-CMOS" cameras together with the Institute of Microelectronics Stuttgart (*ims-chips*). At a deposition temperature as low as 100 °C, we grow flexible solar cells and modules directly on plastic foils which then provide, after integration with clothes, for example, mobile electric power for driving small and portable electronic devices (integrated photovoltaics - *ipv*).

Gruppe Systeme
Group Systems

(Gruppenleiter / Group Leader: Wolfgang Schmitt)

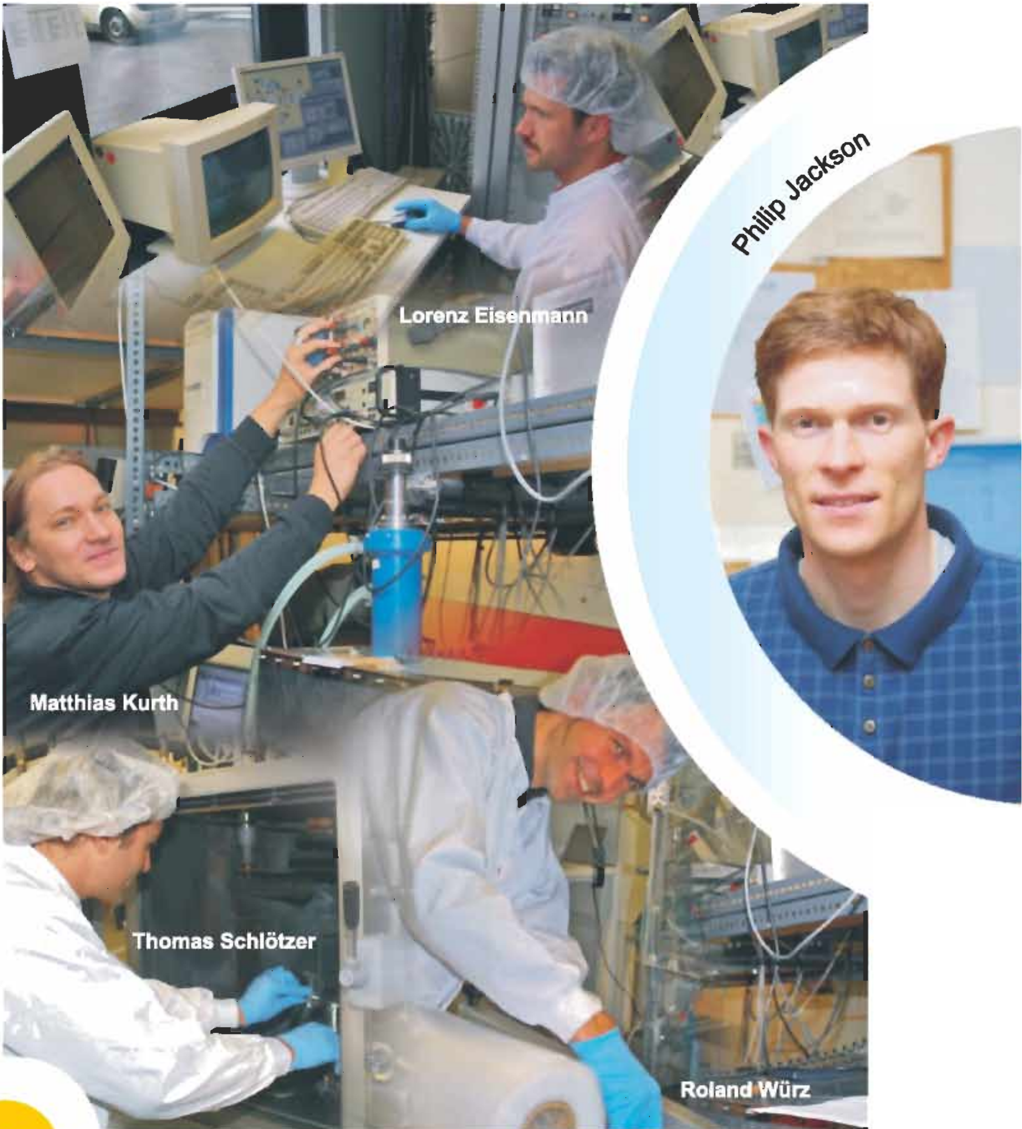


Die Gruppe „Systeme“ befasst sich mit der Systemtechnik elektrischer und elektronischer Geräte und Anlagen. Im Vordergrund stehen dabei sowohl netzgekoppelte als auch netzautarke Photovoltaik(PV)-Anlagen. Ein Schwerpunkt liegt auf der Vermessung, Charakterisierung, Modellierung und Dimensionierung von PV-Systemen und deren Komponenten wie PV-Module, Leistungselektronik sowie der Komponenten zur Energiespeicherung. Außerdem arbeiten wir an der Entwicklung von spezifischen leistungselektronischen Schaltungen (Strom-, Spannungs-, Laderegler) in den Bereichen der kleidungsintegrierten Photovoltaik (*ipv*) und der Energieversorgung von Kleinverbrauchern. Ein aktuelles Forschungsprojekt konzentriert sich auf den Vergleich der Jahresenergieerträge von netzgekoppelten PV-Anlagen unterschiedlicher moderner PV-Technologien (monokristallines, multikristallines und amorphes Silizium, EFG, CdTe, $CuInSe_2$, HIT, Rückseitenkontaktzelle) an drei klimatisch relevanten Standorten (Stuttgart, Kairo, Nicosia).

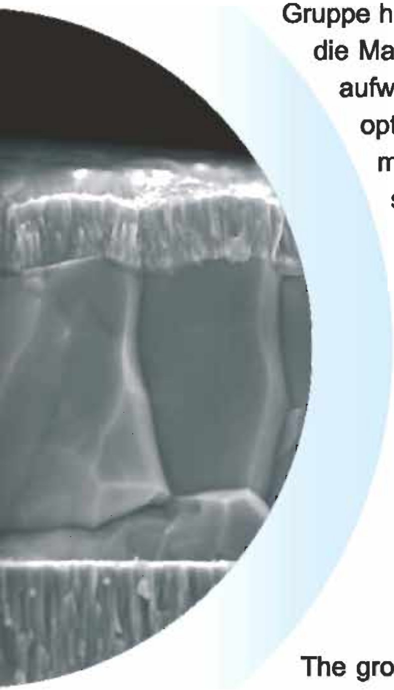
The “Systems” group is concerned with the system technology of electrical and electronic devices. The main interest is laid on grid-connected as well as on grid-independent photovoltaic(PV)-systems. An emphasis is laid on measuring, characterization, modelling and dimensioning of PV-systems and their components as PV-modules, power electronic circuits and systems and electric storage systems. Furthermore we develop specific power electronic circuits (current-, voltage-, and charge-controllers) for clothing integrated photovoltaics (*ipv*) and for the energy supply of small consumers. A recent research project is concentrated on the comparison of the yearly energy yield of different grid-connected PV-systems at three different sites (Stuttgart, Cairo, Nicosia). A number of modern PV-technologies (single crystalline, polycrystalline and amorphous silicon, EFG, CdTe, $CuInSe_2$, HIT, all-back-contact solar cells) is analyzed.

Gruppe Verbindungshalbleiterschichten (CIS)
Group Compound Film Semiconductors (CIS)

(Gruppenleiter / Group Leader: Philip Jackson)



Die Arbeitsgruppe „Verbindungshalbleiter" beschäftigt sich mit Dünnschichtsolarzellen aus dem Halbleitermaterial $Cu(In,Ga)Se_2$ (CIGS). Die Solarzelle besteht aus einem Schichtstapel von Mo, CIGS, CdS, ZnO, Ni/Al-Gridfingern und MgF_2. Als Trägersubstrat wird einfaches Fensterglas verwendet. Bei der Deposition der einzelnen Schichten kommen die Elektronenstrahlverdampfung, die Koverdampfung von Cu, In, Ga und Se, die chemische Badabscheidung, die Kathodenzerstäubung und die Verdampfung aus dem offenen Schiffchen zum Einsatz. Unsere Gruppe hat es sich dabei zum Ziel gesetzt, alle Aktivitäten auf die Maximierung des Wirkungsgrades zu fokussieren. Eine aufwändige Prozesskontrolle sowie die Simulation der optischen und elektrischen Eigenschaften des Bauelements stellen wesentlichen Hilfsmittel für diese Zielsetzung dar.



The group "Compound Semiconductors" aims at the optimization of thin-film solar cells based on the semiconductor $Cu(In,Ga)Se_2$ (CIGS). This solar cell consists of a layer sequence Mo, CIGS, CdS, ZnO, Ni/Al grid fingers, and MgF_2. These layers are deposited on a glass substrate using evaporation and sputtering techniques, as well as the chemical bath deposition. Our work is strictly focussed on the maximization of the power conversion efficiency of these devices. Elaborate process control as well as numerical simulations of the optoelectronic device properties are important tools for the achievement of this goal.

kristallines Silicium

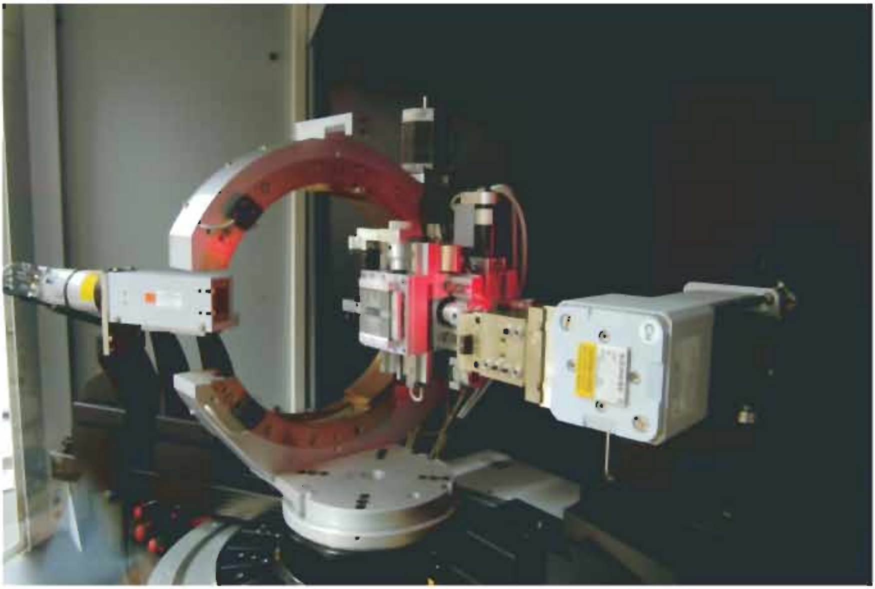
Farbstoffzellen

Verbindungshalbleiter

amorphes Silicium

Wissenschaftliche Beiträge
Scientific Contributions

Publikationen
Publications



Minority carrier lifetime in laser irradiated silicon

Author: M. Ametowobla
In collaboration with: A. Lopez-Ramiro, A. Esturo-Bretón, J. R. Köhler, J. H. Werner

The *ipe* laser doping process [1] is capable of producing shallow, highly doped emitters for silicon solar cells, which recently reached record conversion efficiencies up to η = 17 %. However, the open-circuit voltage of the cells is up to now limited to V_{oc} ≈ 630 mV. One reason for this limit could be the possible generation of crystal defects during the doping process [2].

To gain deeper insight into the influence of the laser irradiation on the electronic quality of the processed samples, we measure the effective minority carrier lifetime τ_{eff}, varying the laser parameters pulse energy density E_p and pulse overlap O_y. In order to minimize the influence due to surface recombination, we deposit a passivating layer of silicon nitride onto the sample surface after the irradiation.

Figure 1 shows the measured τ_{eff} versus E_p for two different values for O_y. Both curves exhibit a significant decrease of the lifetime from τ_{eff} > 200 µs without irradiation to τ_{eff} < 10 µs for E_p = 3.8 J/cm². Especially the O_y = 50 % series reflects the existence of three pulse energy density regimes that apply for laser irradiation: below a threshold E_{th1} no melting of silicon occurs, therefore τ_{eff} remains virtually constant below E_p = 1 J/cm². For $E_{th1} < E_p$ the silicon melts, the melt depth being determined by E_p. In this second regime, starting from E_p ≈ 2 J/cm², τ_{eff} again is unchanged, though reduced compared to the first regime. It ranges between 30 µs < τ_{eff} < 50 µs. As E_p exceeds a second threshold E_{th2} = 3.7 J/cm², the silicon starts to evaporate at the surface, leading to a drastically increased surface roughness (not shown here) and to a sudden drop of the carrier lifetime to τ_{eff} ≈ 5 µs for O_y = 50 %. However, this straight forward correlation does not hold for samples irradiated with O_y = 95 %. Here we do not see the plateau at intermediate E_p values, but rather a continuing decrease of the carrier lifetime with pulse energy density, down to $\tau_{eff} \approx 3$ µs for $E_p = 3.8$ J/cm². This discrepancy between the two series is not yet clarified. However, one reason for the steady decrease at higher overlap possibly is the increased number of melting cycles, $O_y = 95$ % corresponding to 20, $O_y = 50$ % only to 2 melting cycles for every point on the surface. A decrease of τ_{eff} with an increasing number of melting cycles could indicate the creation of crystal defects due to the repeated phase change of the silicon.

These results clearly show an increase in recombination activity due to laser irradiation. Several possible recombination mechanisms need to be considered to explain this effect, among them the formation of crystal defects inside the processed layers. However, also recombination near or at the surface, e.g. due to impurities incorporated from the environment into the liquid silicon, or at the interface between the substrate and the recrystallized layer cannot be ruled out at this stage of research.

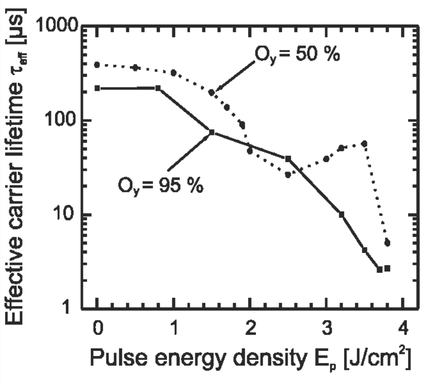


Figure 1:
Effective minority carrier lifetime τ_{eff} of laser irradiated silicon for two different pulse overlap values O_y. For $O_y = 50$ % the curve exhibits three regimes: Virtually constant τ_{eff} for $E_p < 1$ J/cm² and 2 J/cm² $< E_p < 3.5$ J/cm² (though reduced) and a drop of τ_{eff} at E_p = 3.8 J/cm². This coincides with the existence of a melting and an evaporation threshold energy. For $O_y = 95$ % there is no plateau of τ_{eff} for intermediate E_p, indicating a possible deterioration of crystal quality with an increased number of melting cycles.

References:

[1] A. Esturo-Breton, *Emitterdiffusion für Silicium-Solarzellen mittels Laserannealing*, (Diploma thesis, Universität Stuttgart, 2002).

[2] D. L. Parker, F.-Y. Lin, S.-L. Zhu, D.-K. Zhang, W. A. Porter, IEEE Trans. El. Dev. **30**, 1322 (1983).

Low temperature back contact for thin film silicon solar cells

Author: W. Brendle

In collaboration with: V. Nguyen, A. Grohe[1], E. Schneiderlöchner[1], U. Rau, G. Palfinger, J. H. Werner

Our group is specialized in the fabrication of thin monocrystalline silicon films by transfer of epitaxial layers from a host wafer to arbitrary substrates. Solar cells processed into these high quality films reach record efficiencies of more than 16 % on glass and close to 15 % on flexible plastic foils [1]. To further enhance the conversion efficiency of these devices, we need a low temperature back side process that accounts for a good passivation quality, light trapping and a good electronic contact.

Figure 1 shows our newly developed process scheme that fulfills the requirements for high efficiency solar cells. A hydrogenated amorphous silicon (a Si:H) double layer acts as passivation layer. In order to achieve good light trapping, we use a 100 nm thick hydrogenated amorphous silicon nitride film (a-SiN_x:H). Together with a 2 µm thick aluminum layer, the a-SiN_x:H acts as an optical back reflector. The Laser Fired Contact (LFC) process, developed at the Fraunhofer ISE in Freiburg [2], forms the electrical contact. A post deposition anneal for 10 min at T = 220 °C further enhances the passivation quality of the a-Si:H/c-Siu interface.

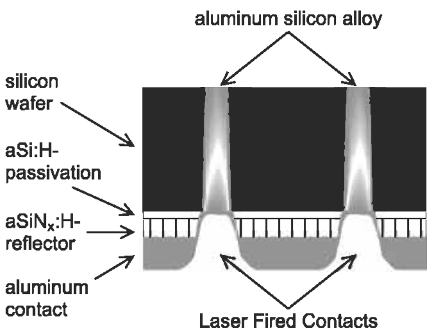


Figure 1:
Scheme of the novel back side structure on a silicon wafer with two Laser Fired Contacts. The a-Si:H double layer for passivation is sketched as a single layer to reduce complexity. Together with the aluminum the a-SiN_x:H acts as back reflector. Laser firing contacts the aluminum back side to the silicon.

[1]Fraunhofer Institut für Solare Energiesysteme (ISE), Freiburg

To show the suitability of this layer system, we fabricate silicon solar cells with a high efficiency front side process on float zone (FZ) wafer material with a resistivity ρ = 1 Ωcm and a thickness W = 250 µm. The back side features our new process scheme. As a reference we use solar cells from the same process with a high quality silicon dioxide (SiO_2) back side passivation and photolithographically defined local point contacts. Table 1 compares the results of a solar cell from the reference process with a cell with our new back side scheme as independently confirmed at Fraunhofer ISE in Freiburg. The main difference between the cells is the fill factor *FF* which is a little lower for the cell with the LFC. However, a closer look shows that *FF* is not restricted by the laser contacts, since it is possible to get values *FF* of *FF* = 78.6 %. Furthermore, the results prove, that the new back side process can compete with the well establish SiO_2 passivation and back side mirror.

Table 1:
Photovoltaic output parameters short circuit current density J_{SC}, open circuit voltage V_{OC}, fill factor *FF*, and efficiency η of a solar cell with the novel back side structure and of a cell with SiO_2 back side passivation. Both cells have an area of A = 1 cm^2 and are fabricated on boron doped FZ wafers with a resistivity ρ = 1 Ωcm and a thickness W = 250 µm. The data are independently confirmed.

cell	J_{sc} [$mAcm^{-2}$]	V_{oc} [mV]	*FF* [%]	η [%]
reference cell	39.9	669	79.4	21.2
new back side	39.9	670	76.5	20.5

References:

[1] C. Berge, T. A. Wagner, W. Brendle, C. Craff-Castillo, M. B. Schubert, J. H. Werner, Mat. Res. Soc. Symp. Proc. **769**, H2.7.1 (2003).

[2] E. Schneiderlöchner, R. Preu, R. Lüdemann, S. W. Glunz, Prog. Photovolt.: Res. Appl. **20**, 422 (2002).

Textured surface on laser created emitter

Author: C. Carlsson
In collaboration with: V. Garcia Garcia, A. Esturo-Bretón, M. Ametowobla, J. Köhler

An important part of the research in the solar cell industry of today is to reduce the manufacturing cost by limiting the number of high temperature steps and clean room necessity. Our previous work [1,2] showed a possibility to create an emitter by laser radiation of a phosphorus rich precursor on silicon. In contrast to conventional diffusion practice, the laser process does not need a high temperature step and also does not need a clean room environment. The previously best solar cells with a laser created emitter had a confirmed efficiency η = 14.2 %. To improve the solar cell efficiency further, a textured surface is necessary, which increases the short circuit current density J_{sc}.

This work shows that it is possible to create an emitter using our laser doping process and still maintain a textured surface. Here we identify the optimal pulse energy density E_p of the laser beam. The pulse energy density E_p must be high enough to create a suitable sheet resistance ρ without destroying the texture.

Figure 1 shows a scanning electron microscope image of the random pyramids after laser processing with a pulse energy density E_p = 1.3 J/cm^2 which results in a sheet resistance ρ = 90 $\Omega/\square$. The pyramids are still present even if the tips on the pyramids start to become spherical.

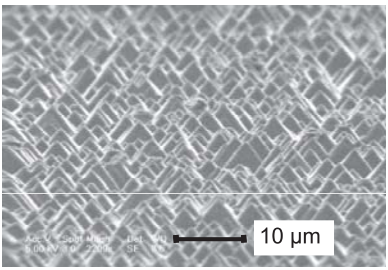


Figure 1:
Scanning electron microscope picture of random pyramids after illumination with a laser beam. With a laser pulse energy density E_p = 1.3 J/cm^2 the pyramids are still present although the laser illumination creates rounder tops.

Figure 2 shows the reflection of a polished silicon surface, random pyramids and random pyramids which are irradiated with a pulse energy density E_p = 1.3 J/cm^2. The spherical tips of the pyramids after laser processing result in a slightly higher reflection.

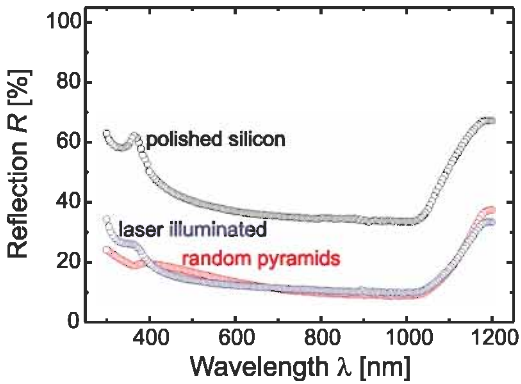


Figure 2:
Reflection measurement from polished silicon, random pyramids and random pyramids after laser illumination with a pulse energy density E_p = 1.3 J/cm^2. The rounded tops of the pyramids give a slightly higher reflection for the laser illuminated sample. However, the reflection is still much lower than the polished silicon.

This work shows that with an applied pulse energy density E_p = 1.3 J/cm^2 it is possible to create an emitter with a suitable sheet resistance of ρ = 90 Ω/□ and still have a textured surface which reduces reflection on the silicon surface significantly.

References:

[1] A. Esturo-Breton, T. A. Wagner, J. R. Köhler, J. H. Werner, in *13th Workshop on Crystalline Silicon Solar Cell Materials and Processes*, Vail (CO, 2003), p. 186.

[2] M. Ametowobla, A. Esturo-Breton, J. R. Köhler, J. H. Werner, in *Proc. 31st IEEE Photovoltaic Specialists Conference (IEEE, Piscataway, 2005)*, p. 1277.

Optimization of the fill factor in solar cells with laser doped emitter

Author: A. Esturo-Bretón
In collaboration with: M. Ametowobla, C. Carlsson, J. Köhler, J. H. Werner

About 95 % of the current commercial solar cells consist of wafer-based mono- or multi-crystalline silicon. Next to the price of the wafer, emitter diffusion is the most important cost factor for the preparation of these solar cells. An important and expensive processing step is the emitter preparation, i.e. phosphorus diffusion into p-type substrates, phosphorus glass etch and edge isolation. The formation of the pn-junctions in diffusion furnaces uses high temperatures in the range of 900 °C. Replacement of diffusion by a simple low-temperature process like laser doping (LD) for the emitter formation has the potential to reduce processing costs considerably.

The first cells processed with the laser doping process developed at our institute reached an independently confirmed conversion efficiency η = 14.2 %. The cells suffered from a low fill factor *FF* due to a high contact resistance r_s between the emitter and front grid.

Optimization steps in the irradiation process reduce the contact resistance and increase the fill factor *FF* up to *FF* = 80.2 %. We measure AM1.5 G efficiencies up to 17.3 % (not yet confirmed) with the optimized laser processing. Figure 1 shows the current/voltage characteristic of two cells scanned with similar laser parameters: pulse energy density and overlap in x- and y-direction between the pulses are identical. Although both samples are scanned with similar processing parameters, the fill factor *FF* of cell 2 which is processed with the optimized irradiation process is significantly higher than the fill factor of cell 1 which is processed with the non-optimized irradiation process. We attribute the slight increase in open circuit to the optimized irradiation process too. Note that the wafer thickness t = 250 µm was reduced for cell 2 from t = 350 µm (cell 1) leading to a somewhat lower short circuit current density J_{sc}.

A simple back contact without V_{oc} surface field is responsible for the relatively low open circuit voltage of both cells. Table 1 compares the solar cell parameters of both cells. The reason for the increase in fill factor llies in a considerably lower series resistance r_s of cell 2 compared to cell 1. The series resistance reduces from $r_s = 1.5\ \Omega cm^2$ for cell 1 to $r_s = 0.24\ \Omega cm^2$ for cell 2.

In conclusion, our novel laser doping process (LD) produces solar cells with electrical conversion efficiencies up to 17.3 % without an expensive high temperature step for the processing of the emitter.

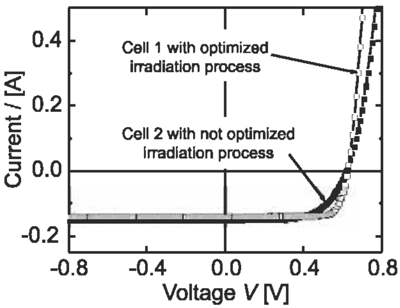


Figure 1:
Cell 1 is processed with the not optimized irradiation process and cell 2 with the newly optimized irradiation process. Although both samples are scanned with similar laser parameters the fill factor *FF* of cell 2 is significantly higher than the fill factor of cell 1. Cell size is 4 cm^2.

Table 1:
Solar cell parameters short circuit current density J_{sc}, open circuit voltage V_{oc}, fill factor *FF*, efficiency η, series resistance r_s and parallel resistance r_p under illumination intensity of 100 mW/cm^2 AM1.5G spectrum. Although both samples are scanned with similar laser parameters, the series resistance r_s of cell 2 is significantly lower than the series resistance of cell 1. The reduction of the series resistance from $r_s = 1.5\ cm^2$ for cell 1 to $r_s = 0.24\ cm^2$ for cell 2 increases the fill factor *FF* and, therefore the efficiency η improves.

cell	J_{sc} [$mAcm^{-2}$]	V_{oc} [mV]	FF [%]	η [%]	r_s [Ωcm^2]	r_p [Ωcm^2]
(1)	35.0	618.7	63.1	13.7	1.5	1.8×10^4
(2)	34.5	623.7	80.2	17.3	0.24	1.1×10^4

(1) not optimized irradiation process, (2) optimized irradiation process

Enhancement of collection and conversion efficiencies of fluorescent collectors by photonic band stop filters

Authors: G. C. Glaeser
In collaboration with: U. Rau, F. Einsele

Fluorescent collectors (FCs) use organic dyes or inorganic fluorescent molecules embedded in a dielectric material to collect and concentrate solar light [1]. The dyes absorb incoming light and emit it at a lower photon energy E. Thereby the direction of the emitted light is randomized and a portion of the light is trapped via total internal reflection as shown in the inset of Fig. 1. Finally, the solar cell collects these photons and converts them into electrical energy.

Here we present a combination of classical FCs with photonic nano-structures for the improvement of photon collection [2]. Figure 1 features the possibility to put a photonic band stop (PBS) filter at the top of the collector. We assume the PBS to be transparent for the incoming light above a certain threshold photon energy E_{th} but to exhibit a reflectance of unity for those photons that are re-emitted from the dye. In this way, 100 % of those photons are kept within the system. Note that practical means to realize PBS with omnidirectional optical reflection in specific wavelength ranges are readily available using technologies that are able to cover large areas, e.g., by one-dimensional periodic dielectric structures, i.e., thin film interference filters.

Figure 1 shows the results of a recent Monte-Carlo analysis of the collection properties of FCs with and without PBS. Here we consider the situation where only radiative losses, as required by the principle of detailed balance, are allowed within the FC *and* the solar cells at its bottom. The coverage fraction f is defined by the portion of the FC's backside that is covered by the solar cells. We see that the system *with* a PBS has a maximum efficiency of η = 33 % at f = 1. This maximum equals the maximum conversion efficiency of a solar cell having a band gap energy E_g that equals the threshold energy E_{th} of the FC.

Thus, even with PBS, FCs cannot overcome the classical Shockley-Queisser limit for photovoltaic energy conversion. However, almost the same efficiency is maintained at a coverage fraction $f = 10^{-2}$, i.e., with a 99 % saving of solar cell material. In contrast, the system *without* PBS has a maximum efficiency of only η = 29 % at f = 1 due to the losses discussed above. Furthermore, with decreasing f, the available η drops sharply such that any saving of solar cell material has to be paid by losses in output power.

The benefit from the use of photonic band structures for this idealized system is obvious. However, more realistic configurations that include also non-radiative losses in the collector as well as in the solar cells exhibit similar efficiency gains by using the spectral selectivity of photonic band structures.

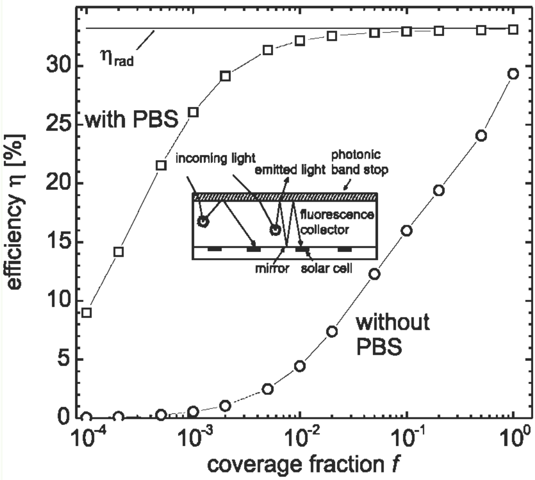


Figure 1: Calculated efficiencies of FCs and ideal solar cells in the radiative limit. Without photonic band stop (PBS) the efficiencies degrade rapidly with decreasing coverage fraction f (circles). With PBS the systems efficiency drops significantly slower with decreasing f (squares), almost maintaining the optimum efficiency down to $f = 10^{-2}$.

References:

[1] A. Goetzberger, V. Wittwer, Sol. Cells **4**, 3 (1988).

[2] U. Rau, F. Einsele, G. C. Glaeser, Appl. Phys. Lett. **87**, 171101 (2005).

Imaging of spatial inhomogeneities in $Cu(In,Ga)Se_2$ solar cells by an electron beam induced voltage technique

Author: P. O. Grabitz
In collaboration with: U. Rau, B. Wille, G. Bilger, J. H. Werner

Thin-film solar cells and modules are large area devices with aspect ratios of up to 10^6. It is rather unlikely that uniform electronic properties of these devices with a thickness in the micrometer-range are maintained over an area of square meters. Instead, we expect spatial fluctuations of the device quality, e.g. caused by composition fluctuations or by the polycrystalline nature of the absorber material. We especially expect spatial fluctuations of the locally available open circuit voltage V_{oc} with significant consequences for the overall conversion efficiency of these photovoltaic devices [1,2].

Here, we introduce an electron beam induced voltage (EBIV) technique for the spatially resolved analysis of these V_{oc} fluctuations in $Cu(In,Ga)Se_2$ (CIGS) solar cells. We use CIGS absorbers grown on a Mo-coated glass substrate and covered with a CdS buffer layer, followed by an insulating SiO_2 layer and an Al contact. A pulsed electron beam generates a local open circuit voltage, that is capacitively coupled to the outer circuit as shown in Fig.1.

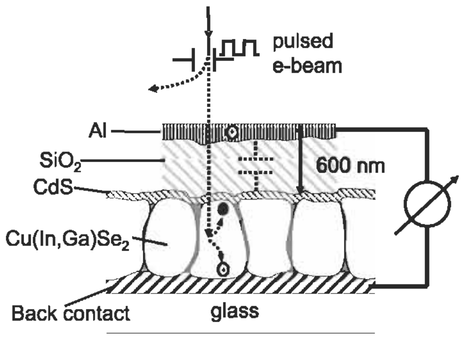


Figure 1:
On a $Cu(In,Ga)Se_2$ absorber layer coated with a 50 nm thick CdS and a SiO_2 layer with a thickness of about 600 nm. A 200 nm polished Al contact provides capacitive coupling to the $CdS/Cu(In,Ga)Se_2$ heterojunction. A pulsed electron beam (frequency ν = 600 kHz, energy of the primary electrons E_{prim}= 25 kV, beam current J_{prim}= 30 pA) generates a local open circuit voltage V_{OC} finally detected by a lock-in amplifier.

The EBIV signal is analyzed by a lock-in amplifier and provides spatially resolved maps of the local open circuit voltage like the one shown in Fig. 2. Bright regions correspond to high V_{oc}, dark ones to low V_{oc}. A histogram (see inset) of the signal heights in Fig. 2 provides the distribution of the EBIV signal V_{EBIV}, which fairly well follows a Gaussian profile with a relative standard deviation $\sigma_{EBIV}/\overline{V}_{EBIV}$ = 15 % where $\overline{V}_{EBIV}$ denotes the mean value of the EBIV signal. The typical cluster size of regions with higher or lower V_{oc} is in the range of 20 to 50 µm. Additional analysis of our Cu(In,Ga)Se_2 samples by spatially resolved energy dispersive X-ray and secondary Ion mass Spectroscopy indicate that the fluctuations are not caused by fluctuations in the Ga-content but rather by a spatially inhomogeneous supply of Na from the glass substrate.

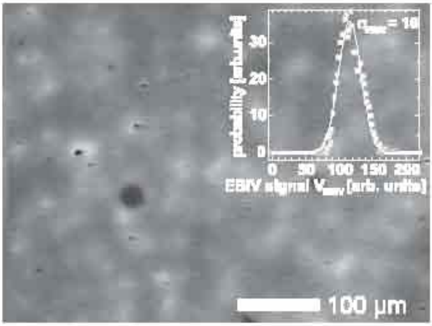


Figure 2:
Mapping of the local open circuit voltage of a CdS/Cu(In,Ga)Se_2 heterostructure obtained by the electron beam induced voltage (EBIV) technique. Bright regions correspond to higher open circuit voltages V_{oc}, dark areas to lower V_{oc}. The inset shows the histogram of the EBIV signals with a fit to a Gaussian distribution.

References:

[1] J. H. Werner, J. Mattheis, U. Rau, Thin Solid Films **480**, 399 (2005).

[2] P. O. Grabitz, U. Rau, J. H. Werner, Thin Solid Films **487**, 14 (2005).

Determination of effective ionic diffusion constants in nano-porous TiO_2 and ZrO_2 networks

Author: M. Hlusiak
In collaboration with: U. Rau, R. Sastrawan[1], R. Kern[1]

Dye sensitized solar cells (DSC) use a network of nanoporous TiO_2 covered by a monolayer of dye molecules [1] to enhance the effective surface area for light absorption. Often an additional ZrO_2 layer is added to enhance light scattering in the DSC. Both porous layers provide a considerable diffusion resistance to the ionic transport of I^-/I_3^- redox couple from and towards the back electrode

Here we use different electrode configurations to measure the effective diffusion constants of I_3^- in the bulk of the electrolyte and within the TiO_2 and the ZrO_2 network (see inset of Fig. 1). The first configuration consists of two Pt-electrodes facing each other with a distance of 46 µm. For the other devices one of the electrodes is covered with nano-porous TiO_2, ZrO_2 layers, or a TiO_2/ZrO_2 double layer. The devices are filled with 0.5 M LiI and 0.05 M I_2 dissolved in acetonitrile and the limiting current densities J_{lim} are determined from the current voltage characteristics shown in Fig. 1. As can be readily seen from Fig. 1 the current density of the device with the 7 µm thick ZrO_2 layer saturates at a lower value than that of the device with the 10 µm TiO_2 layer. The lowest value of J_{lim} stems from the system involving the TiO_2/ZrO_2 double layer.

The quantitative evaluation of the current voltage curves in Fig. 1 is based on the solution of the diffusion equations in a one-, two, and three layer system according to the different electrode configurations [2]. The diffusion constant $D_{T,bulk}$ for the I_3^- ions in the bulk of the acetonitrile solution is $D_{T,bulk}$ = 1.2×10^{-5} cm^{2}s^{-1}. The effective diffusion constant D_{T,TiO_2} within the a TiO_2 network is $D_{T,TiO_2} = 0.47 \times 10^{-5}$ cm^{2}s^{-1}, hence reduced by a factor of

[1]Fraunhofer Institut für Solare Energiesysteme (ISE), Freiburg

0.39 with respect to the bulk value. These two results of our experiments are consistent with earlier investigations [3]. For the ZrO_2 network we find D_{T,ZrO_2} = 0.19 x 10^{-5} cm^2s^{-1}, a value that is considerably lower than that of the porous TiO_2. Thus, transport by ionic diffusion through the ZrO_2 light scattering layer provides a serious limitation to the possible short circuit current density of the DSC, especially when turning to alternative ion transport media like ionic liquids with much lower diffusion constants than in the acetonitrile system.

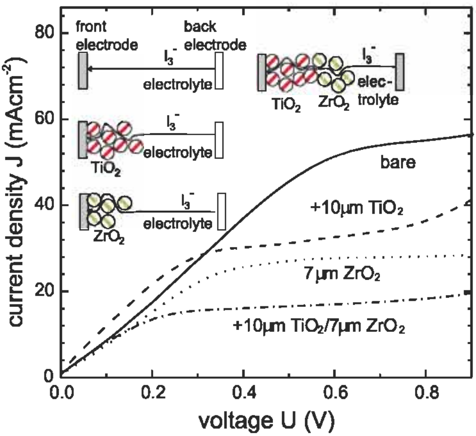


Figure 1:
Current/voltage characteristics of the electrode configurations (two bare Pt-electrodes, one electrode covered with a nano-porous TiO_2, with a ZrO_2 layer, or with a TiO_2/ZrO_2 double layer) as shown in the inset. From the limiting current densities, we calculate a diffusion constant $D_{T,bulk}$ = 1.2x10^{-5} cm^2s^{-1} for the I_3^--ions in the bulk of the acetonytrile solution. The effective diffusion constants within the a TiO_2 and the ZrO_2 are reduced by a factor of 0.39 and 0.19, respectively.

References:

[1] B. O'Regan, M. Graetzel, Nature **353**, 737 (1991).

[2] M. Hlusiak, *Bestimmung von ionischen Diffusionskonstanten in nano-porösen Netzwerken* (Diploma Thesis, University of Stuttgart, Germany, 2005).

[3] G. Kron, U. Rau, M. Dürr, T. Miteva, G. Nelles, A. Yasuda, J. H. Werner, Electrochem. Solid-State Lett. **6**, E11 (2003).

Baseline process for high efficiency $Cu(In,Ga)Se_2$ solar cells

Author: P. Jackson
In collaboration with: R. Würz, M. Kurth, T. Schlötzer, J. Mattheis, J. H. Werner

For the fabrication of $Cu(In_{1-x}, Ga_x)Se_2$ (CIGS) solar cells, a “seven-thin-layer- system”, a large series of process steps is required. For many of the parameters in these processing steps the relevance as well as the degree of dominance are unknown. In such a situation the access to a meaningful experiment is seriously hampered, as parameters that are not strongly dominant can easily be overruled by the collective influence of the experimental noise.

Consequently, we reduce the general noise level in our processes significantly. The reduction of noise in the process also increases the ability to tailor the solar cell device towards an optimal quality level in a much more controlled manner. Therefore, the heart of a high quality baseline standard is a very precise and detailed definition of each process step including the definition of quality standards for every step.

As a thin film solar cell is subject to optical interference, the definition and control of the optimal thickness of each layer is crucial. Consequently, we determine the optical properties of each layer in the system, in order to simulate the optical multi-layer as a whole. The simulation results in a redesign of the optical stack. The thickness of the light-absorbing CIGS-compound semiconductor, for example, is increased by 50 % from 1.8 µm to 2.7 µm, and the ZnO:Al window layer thickness is reduced to a third of its original value – from 300 nm down to 100 nm.

We also redesign the cell and grid geometry with the help of simulation. As a result of the new cell design we observe a significant increase of the shortcircuit current of the cell compared to the old process standard (Fig. 1a), which gives rise to an improved cell efficiency of 19.0 %.

The increase of the thickness of the CIGS absorber, for example, leads to an improvement of the quantum efficiency in the infrared region, which in turn enhances the short circuit current density (Fig. 1b).

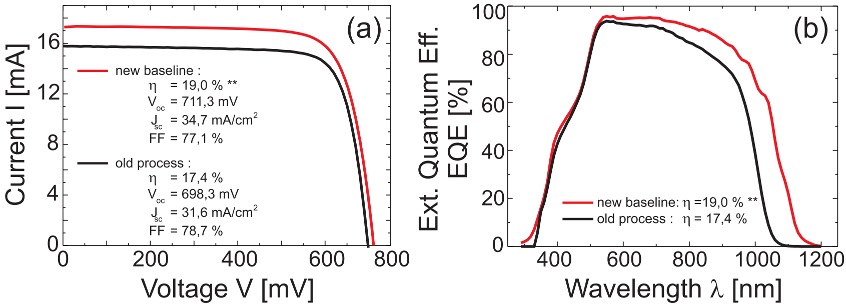


Figure 1:
a) Measured current/voltage-curve for solar cells from the old process and new baseline. Significant gain in short circuit current. b) Measured external quantum efficiency (EQE) for old process and new baseline: Overall improvement of EQE, especially in the infrared region. (**Data confirmed by Fraunhofer ISE.)

The basis for this enhancement of maximum cell efficiency, however, is the overall improvement of process control. The new baseline standard with its average maximum efficiency of 17.7 % ± 0.7 % (Fig. 2) serves as a good base for the success in high efficiency CIGS solar cells.

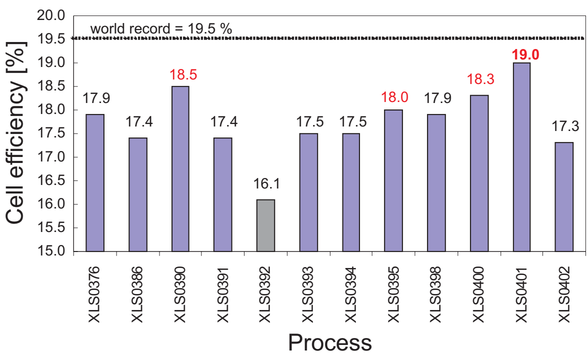


Figure 2:
Maximum efficiencies of consecutive new-baseline runs: The average efficiency is 17.7 %; the standard deviation is ± 0,7 % (absolute) demonstrating the success in process control.

Highly transparent position sensors for alignment purposes

Author: Ch. Köhler
In collaboration with: M. B. Schubert, B. Lutz

During the past few years we developed a technology to produce position sensors for the alignment of detectors in high energy physics experiments. About a dozen of position sensor arrays placed along a propagating laser beam facilitate an adjustment over long distances. The function of such a position sensor array bases upon the matrix readout of analogue photo-conductivity changes in a non-patterned amorphous silicon layer, and provides a sub-µm spatial resolution [1].

Four positions sensors with an active area of 28 x 28 mm^2 each are produced on one 4-inch glass substrate that is coated with an anti-reflection layer on its back side. For the abovementioned setup to work properly, the position sensors must transmit more than 85 % of the incident laser beam at a wavelength of 680 nm. The overall sensor layout comprises two sets of 64 parallel zinc oxide stripes (ZnO:Al, thickness ~ 110 nm) on top, and at the bottom of a non-patterned amorphous silicon carbide (a-SiC:H) layer. The top and bottom sets of ZnO stripes are formed exactly perpendicular to each other. Sandwiched between the stripes, which act as transparent electrodes, the photosensitive a-SiC:H layer is deposited. Both, layer thickness and bandgap of the a-SiC:H are optimized for maximum optical transmittance of the layer stack, and to a high photo-to-dark conductivity ratio. Aluminum bond pads at the ends of the ZnO:Al stripes connect the sensors arrays to the readout electronics.

The sensor matrix shows two major types of electrical defects which strongly deteriorate its performance. The first one is an in-plane connection between parallel stripes (see Fig. 1), while the second type is a vertical short circuit through the layer stack, caused by particles or pinholes, and connecting two (or more) of the orthogonal top and bottom stripes.

Due to electrostatic charging of the glass substrates, the contamination by particles, both inside the thin film deposition systems as well as from the laboratory environment, is the most challenging obstacle to maximum yield and performance. By reducing the number of patterning steps and further measures to reduce the count of detrimental particles, we could significantly increase the overall manufacturing yield.

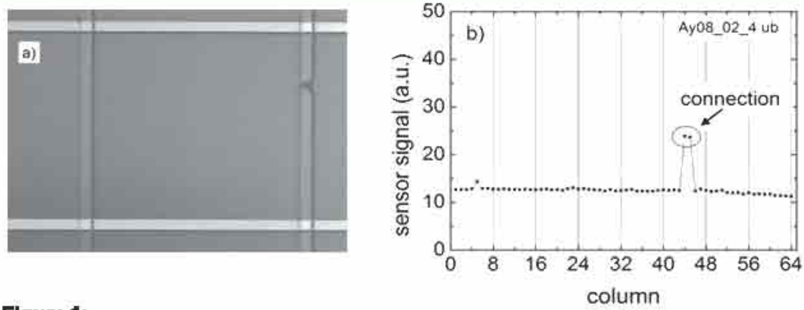


Figure 1:
a) Microscopic view of one pixel out of a 64 x 64 position sensor array. The connection across the gap between adjacent stripes in the upper right corner originates from a contaminating particle during lithographic patterning. b) The electrical test of the sensor performance reveals a doubling of the photo response for the interconnected stripes no. 44 and 45.

Furthermore, we try to repair electrical defects in the the final sensor arrays. So-called "burn-out" is an established method of passivating defects in a-Si:H solar cells. By applying a reverse bias voltage to a large-area diode, heat will be generated locally which can isolate or anneal defects. On the position sensors, however, burn-out experiments fail due to their poor rectification ratio and accordingly high dark conductivity [2].

References:

[1] V. Bartheld, *Entwicklung eines optischen Positionsüberwachungs-systems höchster Präzision für das Myonspektrometer des ATLAS-Detektors am CERN* (Diplomarbeit, TU München, 1997).

[2] P. Schau, *Ausbrennen von Defekten in mikroelektronischen Bauelementen* (Studienarbeit, Universität Stuttgart, 2005).

Analysis of band gap fluctuations in $Cu(In,Ga)Se_2$ thin films by absorption and luminescence measurements

Author: J. Mattheis
In collaboration with: T. Schlenker, M. Bogicevic, U. Rau, J. H. Werner

Polycrystalline semiconductor thin films such as $Cu(In,Ga)Se_2$ feature lateral inhomogeneities in the composition that lead to fluctuations in the band gap of the semiconductor. These band gap inhomogeneities have a strong influence on the open-circuit voltage and on the power conversion efficiency of solar cells [1, 2]. Therefore, it is important to measure and quantify the extent of those fluctuations in polycrystalline materials used for photovoltaic applications.

We investigate the absorption and photoluminescence (PL) of various $Cu(In_{1-x},Ga_x)Se_2$ films by comparing the experiments with the predictions of a simple statistical model [1, 2] that assumes a Gaussian distribution for the fundamental energy gap of the semiconductor. This model has only two free parameters, namely the mean band gap energy $\bar{E}_g$ and the standard deviation σ_g. The model fits absorption and PL data simultaneously and yields a quantitative measure for the band gap fluctuations in terms of the standard deviation σ_g ranging from σ_g = 25 meV to σ_g = 90 meV. The open-circuit voltage losses ΔV_{OC} resulting directly from spatial disorder range from ΔV_{OC} = 10 mV to ΔV_{OC} = 150 mV [3].

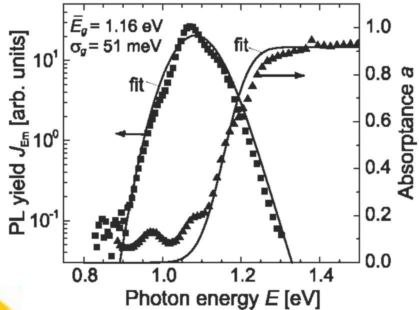


Figure 1:
Measured absorptance and photoluminescence data of a $Cu(In_{1-x},Ga_x)Se_2$ thin film with x = 0.3. Fitting the spectra with Eqs. (1) and (2) from Ref. [3] yields the mean band gap energy $\bar{E}_g$ and the degree of inhomogeneity in terms of the standard deviation σ_g.

Figure 1 displays a measured absorption and PL spectrum together with the theoretical curves obtained from fitting Eq. (1) and (2) from Ref. [3] to the measured data.

Band gap fluctuations lead to a broadening of the absorption edge. Figure 2a shows measured absorption spectra of $Cu(In,Ga)Se_2$ films with different relative gallium content *x*. Our results underline that not only the average band gap $\overline{E}_g$ depends on *x* but also the extent of the band gap fluctuations in terms of the standard deviation σ_g. Figure 2b depicts the standard deviations obtained from fitting Eq. (1) from Ref. [3] to the measured absorption spectra. The fluctuations are maximal for equal amounts of indium and gallium in the film indicating alloy disorder as a possible source of band gap fluctuations.

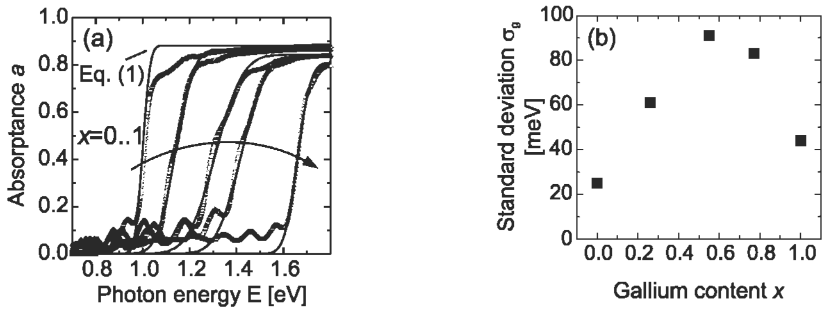


Figure 2:
a) Measured absorption data and fitting curves according to Eq. (1). The absorption edge of $Cu(In_{1-x},Ga_x)Se_2$ thin films strongly depends on the relative gallium content x = Ga/(In+Ga). In contrast to homogeneous direct semiconductors which exhibit a sharp transition edge, the measured films display broadened transitions. b) Standard deviation σ_g of the band gap distribution as obtained from the fits in Fig. 2a. Films with equal amounts of indium and gallium at x = 0.5 exhibit maximum inhomogeneity.

References:

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21 % efficient silicon solar cell with low-temperature a-Si:H/µc-Si/ZnO back contact

Author: P. J. Rostan
In collaboration with: U. Rau, V. X. Nguyen, T. Kirchartz, M. B. Schubert, J. H. Werner

High-efficiency silicon solar cells require back contacts that combine low contact resistance with a low recombination velocity for minority carriers. Usually, these functions are overtaken by a thermally grown oxide combined with photolithographically defined metallic point contacts and the diffusion of a back surface field underneath these local contacts. Cost reduction in processing high efficiency solar cells would be possible if these complicated back contacts could be replaced by a simpler, but equally efficient scheme, preferentially prepared at low temperature.

Here, we introduce a sequence of amorphous (a-Si) and microcrystalline (µc-Si) silicon layers grown by plasma-enhanced chemical vapor deposition (PECVD) at a temperature of 110° C for the passivation of the back surface of Si solar cells. We apply these back contacts to solar cells with diffused emitters and random texture at the front surface. These cells, finished with a full-area a-Si/µc-Si/ZnO contact reach an independently confirmed efficiency of 21.0 % after 10 min annealing at 220 °C [1].

Our solar cells are based on 250 µm thick p-type FZ Si wafers with a resistivity of 1 Ωcm. The cells have a diffused emitter with a random texture as the front electrode, and a photolithographically defined grid. The different back contacts are applied to solar cells with the front side being already fully processed whilst a masking oxide protects the back surface of the wafer. After emitter completion, the back side masking oxide is removed by a dip in 5 % HF solution. Then, the samples are mounted into the PECVD system where we deposit a 10 nm thick undoped (i) a-Si layer followed by an approximately 40 nm thick p-type doped a-Si layer using an admixture of B_2H_6. This deposition uses a temperature $T_S \approx 110$ °C and a plasma frequency ν_p = 13.56 MHz. Next, a heavily p-type doped μc-Si layer (obtained at $T_S \approx 110$ °C and $\nu_p \approx 80$ MHz) with a thickness of about 10 nm is applied to ensure a good ohmic contact to the subsequently sputtered ZnO:Al. Figure 1 shows the photovoltaic output data of our best cell with full-area a-Si/μc-Si/ZnO back contact (cell area A = 1 cm^2). The best cell prepared in this way has an efficiency η = 21.0 % as independently confirmed by Fraunhofer Institute (ISE) Freiburg.

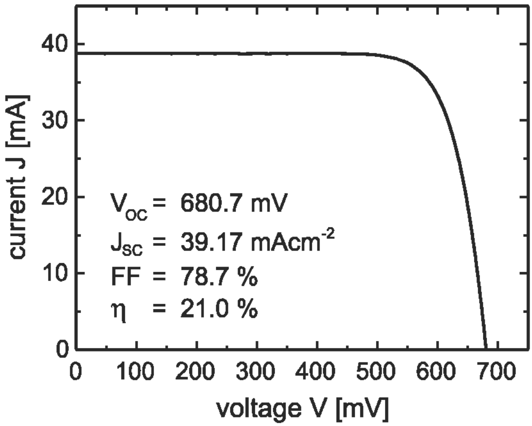

Figure 1:
Current/voltage curve of the best of our Si solar cells with a-Si/μc-Si/ZnO back contact under standard test conditions as measured by Fraunhofer Institute (ISE), Freiburg. The cell area is 1 cm^2, photovoltaic output parameters open circuit voltage V_{oc}, short circuit current density J_{sc}, fill factor FF, and efficiency η are shown.

References:

[1] P. J. Rostan, U. Rau, V. X. Nguyen, T. Kirchartz, M. B. Schubert, J. H. Werner, in *Techn. Digest 15th International Photovoltaic Science and Engineering Conference*, Y. Quinhao, Ed. (Shanghai Scientific & Technical Publishers, Shanghai, China) p. 214.

Optimization of photodetectors for thin film on CMOS cameras

Author: M. B. Schubert
In collaboration with: D. Mader, M. Rakhlin, B. Lutz, C. Harendt[1], E. Penteker[1], J.-D. Schulze-Spüntrup[1], H. G. Graf[1]

The integration of amorphous silicon (a-Si:H) based photodiodes with complementary metal oxide semiconductor (CMOS) circuits greatly enhances the performance of so-called active pixel sensor (APS) or CMOS cameras. Placing a-Si:H based photodiodes on top of the readout electronics, implements almost 100 % area fill factor for the pixel photodiode, and for the underlying electronics as well. Consequently, sensitivity and modulation transfer function of such "Thin-Film-on-CMOS" (TFC) systems clearly outperform those of regular APS cameras. Manufacturing of complete TFC camera chips with linear or logarithmic readout characteristics is performed in a close and well-established cooperation between the Institute of Microelectronics Stuttgart (*ims-chips*) and our institute.

One of the keys to high performance of TFC cameras is the interplay between the layout of the thin film photodiodes and the input of the pixel amplifier or readout circuitry. Depending on the target application, different photodiode structures are needed. Figure 1a demonstrates significant differences in the sensitivity of *p-i-n* versus *n-i-p* layer sequences, as measured by their external quantum efficiency [1]. With the light entering from the *p*-side, the *p-i-n* photodiode performs much better since in a-Si:H based semiconductors the effective electron mobility is a factor of 10 to 100 larger than the hole mobility. The collection of holes is therefore limited to the vicinity of the *p/i* interface, and most photogenerated holes recombine on their way to the *p*-type back contact of the *n-i-p* structure depicted at the bottom of Fig. 1a. As expected, hole collection can be slightly improved by raising the readout voltage from V = -2 V to V = -3 V which is, however, the limit set by the supply voltage of the current CMOS technology.

[1]*ims-chips*, Stuttgart

Some applications, e.g. radiation hard readout circuits, enforce the use of a *p*-type back contact, and hence a *n-i-p* layer sequence with the light unfavorably entering from the *n*-side. For such configurations, Fig. 1b evaluates the amount of improvement attainable by careful tuning of the *i*-layer thickness. Due to readout noise considerations, the capacitance of the thin film photodiode should be as high as possible, asking for thick *i*-layers. Figure 1b demonstrates a significant enhancement of carrier collection if the *i*-layer is kept thin enough to allow for successful extraction of the photogenerated holes, and thereby presents a viable compromise in the optimization of sensitivity versus noise reduction.

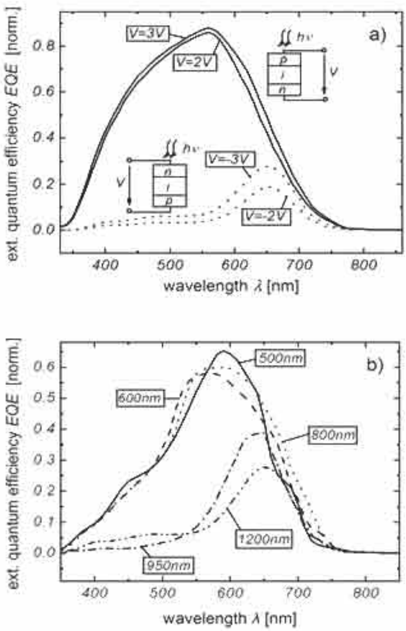

Figure 1:
(a) External quantum efficiency EQE measurements on thick TFC diodes reveal the breakdown of charge carrier collection in n-i-p structures where the light enters through the n-type doped layer. In contrast, the response of p-i-n diodes nicely resembles the spectral sensitivity of the human eye, and peaks at values above 80 %. The i-layer thicknesses of the n-i-p and p-i-n diodes amount to 1.2 µm, and 1.5 µm, respectively.
(b) The thickness dependence of EQE in n-i-p photodiodes proves that an optimum thickness of 700 nm can indeed be used for n-i-p TFC layer stacks. Larger i-layer thickness clearly hinders hole collection in those structures.

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Integrated photovoltaic mini-modules of thin film mono-crystalline silicon solar cells

Author: O. Tobail
In collaboration with: P. K. Khanna, P. J. Rostan, K. Brenner, M. B. Schubert, J. H. Werner

We introduce a new method to fabricate integrated photovoltaic mini-modules based on thin film monocrystalline Si solar cells. Transfer cells with a thickness of 50 µm are produced by a Quasi Mono-crystalline Silicon (QMS) process which is developed at our institute [1]. These cells are transferred onto glass superstrates and the host wafer can then be reused. In this method, we make use of a pulsed excimer laser to process the transferred cells and connect the cells in series to get higher voltages.

For solar cell fabrication, the absorber film is epitaxially deposited at temperature of 1100 °C. The epitaxial growth is accomplished in two steps, starting with a 1.5 µm thick p^+-layer with a boron doping density of $N_A = 1\times10^{19}$ cm^{-3} that serves as a back surface field (BSF), followed by the deposition of about 50 µm p-absorber layer with a boron doping density of $N_A = 1\times10^{17}$ cm^{-3}. The BSF is important in our cells to avoid recombination in the QMS film. The processing sequence for solar cells established at *ipe* makes use of standard *pn*-junction technology for solar cell fabrication.

Solar cells with thickness of 50 µm are fabricated and successfully transferred onto glass substrates. We transfer 4 cells each of area $A = 4$ cm^2 onto one glass superstrate, then make use of the excimer laser to connect the 4 cells in series. First, we separate the cells electrically by laser scribing, and then we drill holes through the silicon to reach the front contact from the back side. These holes must be outside the cell region, so we attach silver stripes to the front contact busbar and leave the other side of it hanging outside the cell. The connection of cells is accomplished by dispensing an epoxy (conducting glue) starting from the back contact of one cell to the hole which represents the back contact of the other cell.

With this technology, we have fabricated a first PV module of area $A = 18.5$ cm^2 with an efficiency $\eta = 8.1$ % . The measured current/voltage characteristics under illumination by spectrum similar to AM 1.5 G is shown in Figure 1. The measured open circuit voltage V_{oc} is $V_{oc} = 2.14$ V and the short circuit current I_{sc} is $I_{sc} = 129$ mA which corresponds to short circuit current density of $J_{sc} = 32.3$ mA/cm^2.

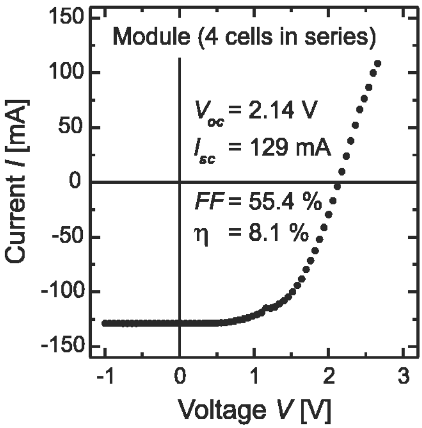

Figure 1:
Measured current/voltage characteristics of the module under illumination by a spectrum similar to AM 1.5 G. The total area of the module is 18.5 cm² while each cell has an area of 4 cm². Photovoltaic output parameters open circuit voltage V_{oc}, short circuit current I_{sc}, fill factor *FF*, and module efficiency η are given.

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Lehrveranstaltungen
Lectures

Bauelemente der Mikroelektronik (1. Semester)

Energiebänder und Leitfähigkeit

Silicium - der Werkstoff der Mikroelektronik

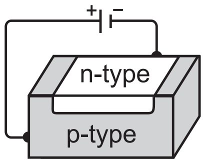
Elektronen und Löcher in Halbleitern

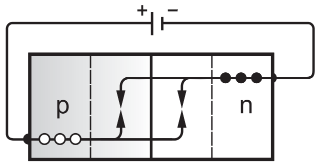
Ströme in Halbleitern

Nichtgleichgewicht und Injektion

Elektrostatik des pn-Übergangs

Ströme im pn-Übergang





Energiewandlung (6. / 8. Semester)

Grundlagen der Kernenergie

Thermodynamik

Direkte Nutzung der Sonnenenergie (Solarthermie, Photovoltaik)

Indirekte Nutzung der Sonnenenergie (Wasserkraft, Windenergie)

Chemische Wandlung und Speicherung elektrischer Energie

Laser and Light Sources (5. / 7. Semester)

The Human Eye

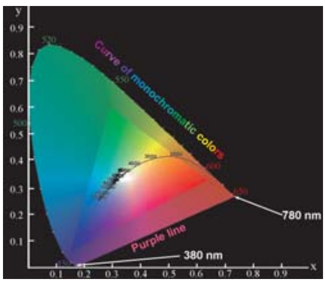
Light and Color

Photometry

Incoherent Light Sources

Light Emitting Diodes

Lasers



Optoelectronic Devices and Circuits I (6. / 8. Semester)

Basic physics

Thermal radiation

Coherence

Semiconductor basics

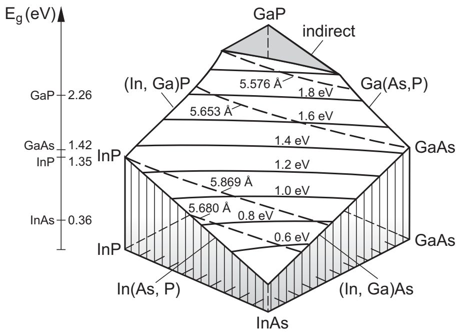
Excitation and recombination processes in semiconductors

Light emitting diodes

Semiconductor lasers

Glass fibers

Photodetectors



Photovoltaics (6. / 8. Semester)

Energy data

The solar spectrum

Potential of solar radiation

The principal function of photovoltaic systems

Generation and recombination in semiconductors

Basic semiconductor equations

pn-Junctions

Current/voltage-curve of solar cells

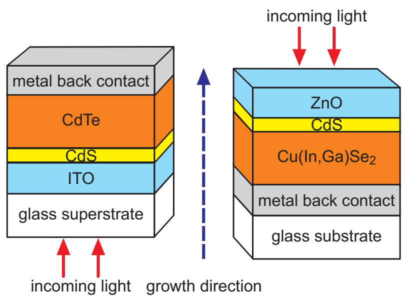
Maximum efficiency of solar cells

Preparation of crystalline silicon

Amorphous silicon solar cells

$Cu(In,Ga)Se_2$ solar cells

Technology of crystalline silicon solar cells



Solid State Electronics (5. / 7. Semester)

Free electrons as particles and waves

Electronic bands in solids

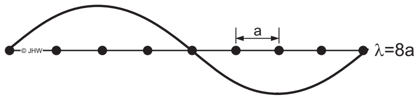
Band diagrams of semiconductors

Currents in semiconductors

Emission of electrons from metals and semiconductors

The Schottky-contact

Photoeffects in semiconductors



Promotionen
Ph. D. Theses

Diplomarbeiten
Diploma Theses

Studienarbeiten
Major Term Projects

Gäste & ausländische Stipendiaten
Guests

Promotionen

Ph. D. Theses

Thomas G. Schlenker
Growth of $Cu(In,Ga)Se_2$ thin films

Diplomarbeiten

Diploma Theses / Master Theses

Anas Al-Tarabsheh
Preparation of amorphous silicon (a-Si:H) solar cells and characterization under different illumination levels

Martin Bogicevic
Optische Inhomogenitätsuntersuchungen an $Cu(In,Ga)Se_2$-Absorberschichten

Martin Braun
Models for transient simulations of decentral power generation – implementation and verification in PowerFactory

Caroline Carlsson
Annual irradiance gain of two- and three dimensional static concentrating troughs

Miguel Angel Domínguez
Optimization of the contact resistance in laser doped solar cells

Markus Hlusiak
Bestimmung von ionischen Diffusionskonstanten in nanoporösen Netzwerken

Rolf Jochen Kaiser
Untersuchung zur Realisierbarkeit photonischer Bauelemente mit amorphem Silicium, Siliciumkarbid und –nitrid

Albrecht Kern
Optimierung der Passiviereigenschaften dielektrischer Schichten auf Silizium

Aida López Ramiro
Optimierung der Oberflächenpassivierung laserprozessierter Solarzellen

Denis Mader
Optimierung von Thin-Film on CMOS Photodioden

Rainer Merz
Serienverschaltung flexibler Solarzellen für Kleidungsintegration

Michael Reuter
Elektronische Metastabilitäten in Cu(In,Ca)Se_2-Solarzellen

Osama Tobail
Analyse der Verluste in Cu(In,Ga)Se_2-Solarzellen

Christof Wagner
Solareigenschaften unter praxisnahen Temperatur- und Beleuchtungsbedingungen

Bernd Wille
Messung elektronenstrahlinduzierter Ströme und Spannungen

Bastian Zinßer
Netzgekoppelte Photovoltaik-Anlagen verschiedener Technologien mit internetbasierter Datenerfassung und Überwachung

Studienarbeiten

Major Term Projects

Agnes Berger
Flexible Solarzellen und –module aus amorphem Silizium

Christian Ehling
Nachweis der Lichtkonzentration in Fluoreszenzkollektoren mit optischer Bandsperre

Florian Einsele
Sammlungs- und Konversionseffizienz von fluoreszierenden Farbstoffschichten

Sebastian Eisele
Untersuchung und Optimierung der Laserdotierung mit gesputterten Dotierschichten

Florian Etter
Entwicklung einer Ladeschaltung für Lithium-Ionen-Akkumulatoren

Claudia Gatzert
Analysis of reactive ion etching of dielectrics and Si in CF_3/O_2 and DF_3/Ar

Matthias Geiger
Strom-/Spannungs- und Kapazitäts-/Spannungsanalyse von aSi/cSi Heterostrukturen

Thomas Kirchartz
Analyse von Heterosolarzellen aus amorphem und kristallinem Silizium

Swen König
Charakterisierung von fluoreszierenden Farbstoffschichten

Philipp Schau
Ausbrennen von Defekten in Solarzellen und mikroelektronischen Bauelementen

Hongwu Tu
Simulation der Lichtsammlung in sphärischen Solarzellen

Na Wei
Influence of the intrinsic ZnO layer on inhomogeneous $Cu(In,Ga)Se_2$ solar cells

Gäste & ausländische Stipendiaten
Guests

Anas Al Tarabsheh
Jordan University of Science and Technology, Jordanien (seit 01.03.03)

Ainhoa Esturo Bretón
UPV-Universidad del Pais Vasco, Spanien (seit 01.12.2001)

Caroline Carlsson
Göteborgs Universitat, Schweden (seit 01.03.03)

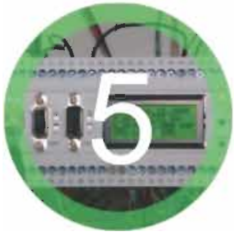
Xuan Viet Nguyen
National Center for Natural Science and Technology, Hanoi, Vietnam (seit 01.11.2001)

Obed Opoku
KNUST University in Kumasi, Ghana (01.08.–30.11.05)

Jesús Rebollar Naveiro
E.T.S.I.T., Universidad Politécnica de Madrid, Spanien (15.05.–15.11.05)

Osama Tobail
Arab Academy for Science and Technology & Maritime Transport, Alexandria, Ägypten (seit 01.07.03)

Chuanming Xu
Nankai University, Tianjin, China (31.07.–26.10.05)



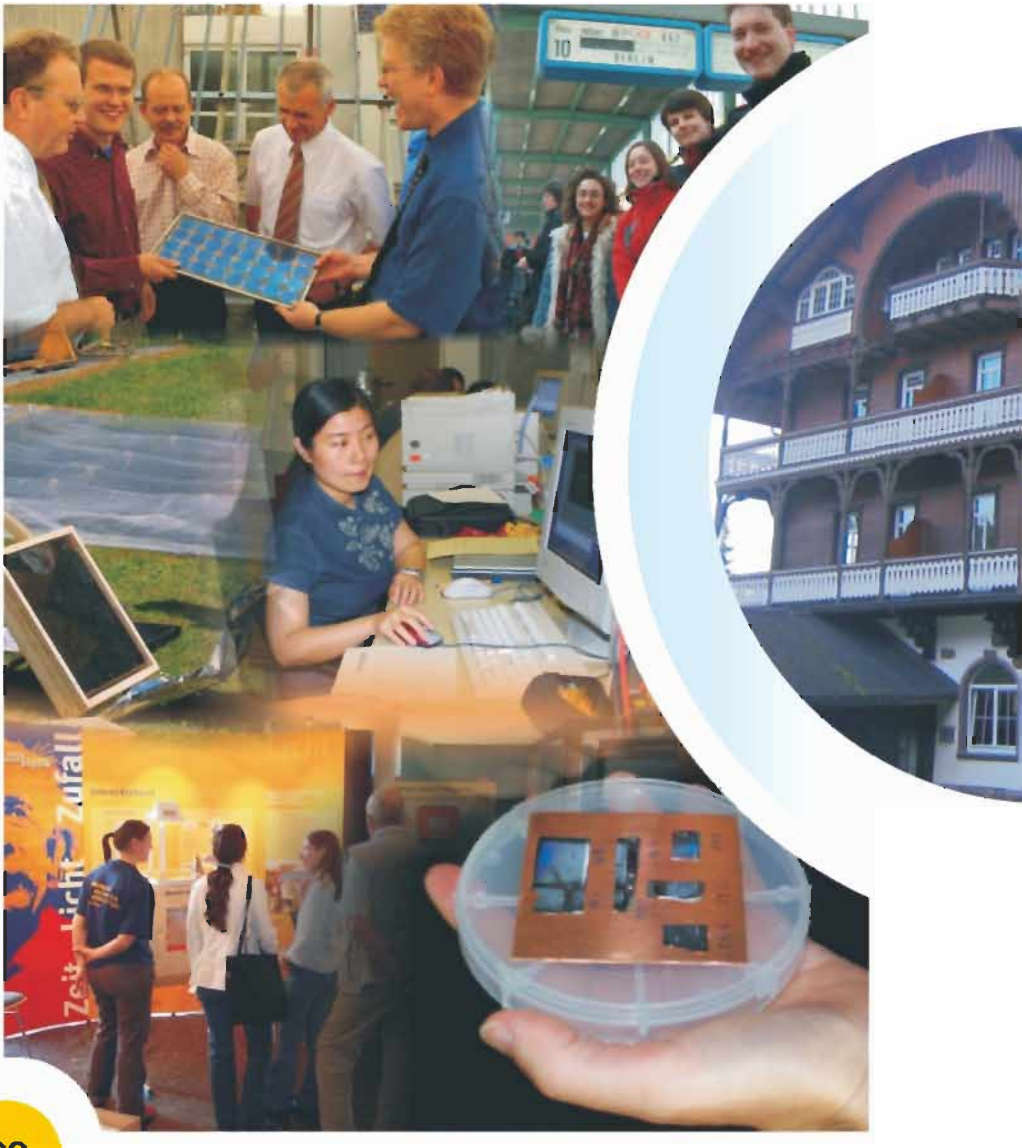
Was sonst noch war ...
More than Science ...

Mitarbeiterliste
Staff Members

Lageplan
Location Map

Was sonst noch war ...
More than Science ...

(Christine v. Rekowski)



Dr. Nick-Leptin vom BMU und Dr. Bastek vom PTJ konnten sich von Projektfortschritten überzeugen, und so hoffen wir, dass zahlreiche weitere förderwürdige Folgeprojekte unterstützt werden können.

Mögliche Kooperationsprojekte mit China führen zu regelmäßigen kurzen und langfristigen Aufenthalten von Gastwissenschaftlern am *ipe*, die uns immer willkommen sind. Überhaupt strecken sich die internationalen *ipe*-Fühler immer weiter aus, so dass das *ipe*-Team bunt bleibt und die Mitarbeiter Weltluft schnuppern können. So verbrachte „unser“ Julian 4 Monate in Oregon in den USA, wo er einen bereichernden Austausch mit US-Kollegen genoss.

Nicht nur in den zahlreichen Forschungsprojekten, sondern auch während den Vorlesungen wird die Kreativität der *ipe*-Mitarbeiter bzw. Studenten angeregt.

We welcomed VIP visitors from the German Ministry of Environment and the Research Centre Jülich, who had a look at the achieved progress of different projects. We hope that several more new projects will be supported soon.

Possible cooperation projects with China lead to regular long and short term stays of guest scientists at *ipe*. We enjoy having an international team, and *ipe* goes on making up its own “world network”. Our staff member Julian stayed 4 months in Oregon, USA, where he was able to have a look at different scientific approaches.

Not only in the several research projects, but also during lectures, *ipe*-staff members and *ipe* students are invited to be creative. In order to get credits for the lecture “energy conversion”, the candidates had to build own prototypes that were able to demonstrate solar power, offering barbecued sausages and fried eggs to the audience.

Wer die Vorlesung „Energiewandlung“ belegt hatte, konnte spektakuläre Energiedemonstrationen vorführen und beispielsweise mit Sonnenenergie gebratene Spiegeleier oder Würstchen servieren. Was eignet sich zur dieser Demonstration effektiv umgesetzter Sonnenenergie besser als der Besuch einer Stuttgarter Grundschulklasse, die sich ganz konkret vom *ipe* erklären ließ, was Sonnenenergie überhaupt ist. Institutsleiter J.H. Werner wurde in die Lage des Grundschullehrers versetzt und schlug sich wacker!

Die diesjährige Exkursion mit knapp 30 Teilnehmern führte in den Osten der Republik, wo die Firmen AMD und Infineon in Dresden sowie die Deutsche Solar in Freiberg besichtigt wurden.

Das *ipe* hat schon immer gerne Wissenschaftliches mit Gesellschaftlichem verbunden, z.B. während der regelmäßig anstehenden Konferenzen im In- und Ausland, zu denen *ipe*-Mitarbeiter zur aktiven Teilnahme aufgefordert werden. Erfahrungsgemäß schweißen diese gemeinsamen Reisen zusammen.

A special demonstration of solar power was offered to a primary school class visiting us, so that institute director J. H. Werner temporarily became a primary school teacher doing pretty well!

This time, the yearly excursion took nearly 30 participating students to the eastern border of Germany, where they visited the companies AMD, Infineon and Deutsche Solar in Dresden and Freiberg. Combining scientific matters and social gathering is a matter of course, for example during conferences abroad or in Germany, to which *ipe*-staff members are invited to participate regularly.

Own outstanding ipe-achievements are always an occasion to celebrate, for example after having produced a 21 %-cell.

Eigene überragende Forschungsergebnisse werden auch gerne mit Sekt begossen, vor allem, wenn neue Rekorde erstellt werden konnten, wie z.B. die Herstellung einer 21%-Zelle.

Seit langer Zeit fand im September wieder einmal eine zweitägige Gesamt-*ipe*-Tagung in Lauterbad (Schwarzwald) statt, wo neben allgemeinem Austausch auch die Freizeitaktivitäten nicht zu kurz kamen.

Auch die Studenten, die ihre Arbeit am *ipe* einreichen, treffen sich in regelmäßigen Abständen mit dem Institutsleiter, um Anregungen und Kritik in einem informellen Rahmen zu besprechen. Übrigens konnte sich das *ipe* dieses Jahr beim ETI-Cup einen ruhmreichen Vizemeister-Titel erkämpfen eine beachtliche Leistung! Herzlichen Glückwunsch an alle Team-Mitglieder.

In diesem Sinn wünscht das *ipe* seinen Mitarbeitern ein engagiertes und positives Weiterarbeiten.

As a special event, the whole ipe was invited in September to get together for two days in the Black Forest, where we had some scientific exchange besides plenty of time for recreation, long walks and good talks.

Students working at the *ipe* get together with J. H. Werner informally once or twice a year, in order to discuss the situation at the institute. During these meetings, proposals and criticisms are always welcome.

This year's *ipe*-Soccer-Team fought in a fantastic way during the ETI-Cup Tournament and was rewarded, becoming the runner-up. Congratulations to all the players!

In that sense, *ipe* wishes its staff members a good follow-up for the coming year!

Mitarbeiterliste

Staff Members

Name	Titel	Telefon 0711 - 685 - ...	E-Mail ... @ipe.uni-suttgart.de	Arbeitsgebiet
Al Tarabsheh, Anas Ibrahim	M. Sc.	7179	anas.al-tarabsheh	Optimierung und Charakterisierung von amorphen Silicium-Solarzellen
Ametowobla, Mawuli	Dipl.-Ing.	7160	mawuli.ametowobla	Laserprozessierung von Silicium-Solarzellen
Bauer, Leo		7182	leo.bauer	Metallisierung, Photoarbeiten, Maskentechnik
Bilger, Gerhard	Dr.-Ing.	7176, 7154	gerhard.bilger	Oberflächenanalytik mit SIMS und XPS; Technologie Support
Brendle, Willi	Dipl.-Ing.	7178	willi.brendle	Niedertemperatur-passivierung für Transfer-Solarzellen
Brenner, Klaus	Dipl.-Ing. (FH)	7201	klaus.brenner	Technologische Infrastruktur und Prozesse der Si-Technologie
Carlsson, Caroline	M. Sc.	7160	caroline.carlsson	Laserprozessierung von Silicium-Solarzellen
Dür, Jenny		7158	jenny.duer	Verwaltung
Esturo-Bretón, Ainhoa	M. Sc.	7169	ainhoa.esturo-breton	Laserprozessierung von Silicium-Solarzellen
Gläser, Gerda	Dipl.-Ing.	7168	gerda.glaeser	Charakterisierung von Monograin-Solarzellen
Grabitz, Peter	Dipl.-Phys.	7197	peter.grabitz	Flexible Verbindungshalbleiter-Solarzellen

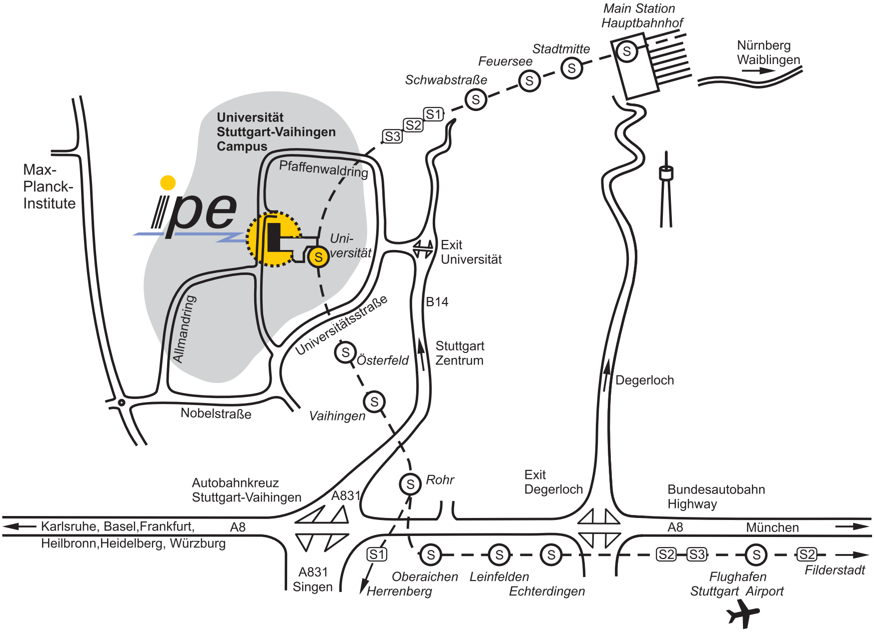
Gräter, Lydia		7163	lydia.graeter	Sekretariat, Verwaltung, www
Jackson, Philip	Dipl.-Phys.	7198	philip.jackson	Flexible Substrate
Kessler, Isabel	M. A.	7141	isabel.kessler	Sekretariat, Verwaltung
Kurth, Matthias	Dr. rer. nat.	7142	matthias.kurth	Temperatur- und leistungsabhängige Photolumineszenz-Messungen an Halbleitern
Köhler, Christiane	Dipl.-Phys.	7182	christiane.koehler	Si-Niedertemperaturtechnologie, XRD, transparente Kontakte, Ramanstreuung
Köhler, Jürgen	Dr.-Ing.	7159	juergen.koehler	Laser Annealing,Verwaltung
Laptev, Viktor	Dr. rer. nat.	7197	viktor.laptev	Chemische Schichtabscheidung, Röntgenbeugungsmessungen
Lutz, Brigitte		7200	brigitte.lutz	Analytik, Elektrochemie, GCMS
Mattheis, Julian	Dipl.-Ing.	7161	julian.mattheis	Optische Eigenschaften von Solarzellen
Merz, Rainer	Dipl.-Ing.	7184	rainer.merz	Solarzellen und Module für integrierte Photovoltaik
Nguyen Xuan, Viet	M. Sc.	7179	viet.nguyen	a-Si:H/c-Si Heterostrukturen
Palfinger, Günther	Dipl.-Ing.	7180	guenther.palfinger	Projektleitung dünne monokristalline Silizium Solarzellen, Intranet
Rau, Uwe	Dr. rer. nat. habil.	7199	uwe.rau	Elektr. Charakterisierung von Dünnschichtsolarzellen Gruppenltg. "Bauelemente"

Reuter, Michael	Dipl.-Ing.	7168	michael.reuter	Einseitig kontaktierte Solarzellen
Riß, Anton		7214	anton.riss	Werkstatt
Rostan, Johannes	Dipl.-Ing.	7179	hannes.rostan	a.Si:H/c-Si Heterostrukturen
Schmitt, Wolfgang	Dr.-Ing.	7171	wolfgang.schmitt	Photovoltaische System-technik, Leistungselektronik
Schubert, Markus	Dr.-Ing.	7145	markus.schubert	Projektleiter amorphes und nanokristallines Si, Solar-zellen mit Sensoren,Studien- und Diplomarbeiten, www
Sprengel, Wolfgang	Dr. rer. nat.	7168	wolfgang.sprengel	Neue Materialien
Tobail, Osama	Dipl.-Phys.	7183	osama.tobail	Verlustanalyse von CIGS-Solarzellen
v. Rekowski, Christine	Dr. phil.	7141	christine.rekowski	Sekretariat, Verwaltung
Werner, Jürgen	Prof. Dr. rer. nat. habil.	7140	juergen.werner	Institutsleiter, Leitung der Forschung, Lehre, Verwaltung
Wille, Werner		7158	werner.wille	Buchhaltung, Verwaltung
Winter, Birgitt	Dipl.-Ing.	7162	birgitt.winter	Technologie kristalliner Si-Solarzellen
Würz, Roland	Dr. rer. nat.	7171	roland.wuerz	Dünnschichtsolarzellen aus kristallinem Silizium
Zinßer, Bastian	Dipl.-Ing.	7170	bastian.zinsser	Jahresenergieerträge verschiedener Photovoltaik-Technologien

Stand 12/05

Lageplan

Location Plan



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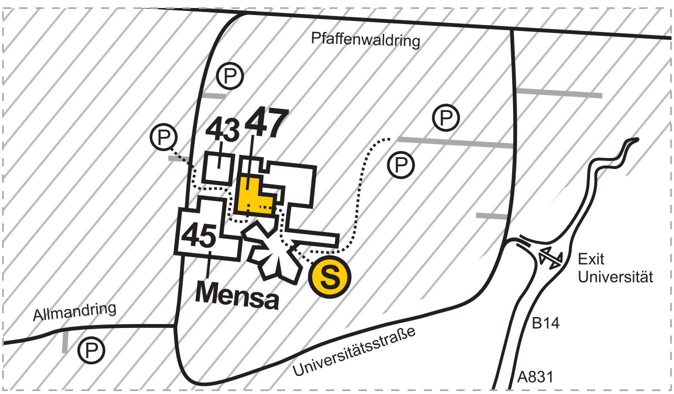

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