Institut für Photovoltaik

Institute for Photovoltaics

Universität Stuttgart

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Annual Report 2011
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Annual Report 2011

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Vorwort

Liebe Freunde des Institut für Photovoltaik,

der Unfall in Fukushima hat fast jedem klar gemacht, dass nur erneuerbare Energien dazu in der Lage sind, eine nachhaltige Energieversorgung zu garantieren. Für das Stromnetz wird dabei Photovoltaik in Zukunft eine wichtige Rolle spielen. Im ersten Halbjahr 2011 hat die Photovoltaik mit 3,8 % mehr zum Bruttostrom Deutschlands beigetragen als die Wasserkraft.


Ich danke allen Mitarbeiterinnen und Mitarbeitern des ipe und des ipv für ihr großartiges Engagement.

Stuttgart, Dezember 2011

Jürgen H. Werner
Preface

Dear friends of the Institute for Photovoltaics,

the accident in Fukushima made clear to almost everybody that only renewable energies guarantee a sustainable energy supply for mankind. In case of electricity supply, photovoltaics will play a significant role in the future. With more than 3.8 %, in the first half of the year 2011, photovoltaics contributed more to German electricity supply than water power.

With the new name “Institut für Photovoltaik” (ipv) the story of the “Institut für Physikalische Elektronik” (ipe) ends after more than 60 years. Under the new name, we will even improve and enhance our efforts to contribute to the development of not only better solar cells, but also systems, and applications of photovoltaics and a real green electricity grid. We expect that the “Solarzentrum Stuttgart” a new cooperation project between the ipv and the Steinbeis Center Applied Photovoltaics, will contribute to these goals.

I am grateful to all coworkers of the ipe and ipv for their excellent work.

Stuttgart, December 2011

Jürgen H. Werner
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Verwaltung • Administration
Gruppe Laserprozesse
Group Laser Processing

(Gruppenleiter / Group Leader: Jürgen Köhler)

The "Laser Processing" group explores new technologies for laser processing of mono- and multocrystalline silicon wafers. Examples are laser assisted metal deposition, laser edge isolation as well as laser doping for full area and selective emitters of crystalline silicon solar cells. The main topic of our research work is the investigation of the fundamental processes involved in pulsed laser doping as well as in laser assisted fine line metallization of 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 up to 156 mm x 156 mm sized mono- and multi-crystalline silicon solar cells to more than 18.5 %. A close collaboration with the "Industrial Solar Cells" group at ipv optimizes our selective-emitter laser-doping process together with screen printing technology for high efficiency mono- and multi-crystalline silicon solar cells.
Gruppe Technologie
Group Technology

(Gruppenleiterin / Group Leader: Birgitt Winter)

The group “Technology” pools all technical assistants and engineers. It supports the laboratory infrastructure, perform the different standard processes and do routine measurements. The cross linking of technical experience allows an effective coordination of the requested demands. We make standard analyzes, upgrade measurement setups, coordinate the reconstruction of the laboratory and improve technical processes. We especially work on oxidation, diffusion, plasma enhanced deposition, wet chemical cleaning and etching, lithography and metallization. All techniques have to be adapted and developed in direction of requirements of the current scientific projects at ipv. Our goal is a high reproducibility of all process steps by developing quality control requirement and standard procedures. A close teamwork on planning and discussion of the results is seen as a proper base.
Gruppe Dünnschichtsilizium
Group Thin Film Silicon

(Gruppenleiter / Group Leader: Markus Schubert)

The “Thin Film Silicon” work group at ipv is developing solar cells and photodetectors based on amorphous and nanocrystalline silicon thin films. Flexible photovoltaic modules prove the novel in situ series connection technique. Low temperature processes deposit ultrathin amorphous silicon layers for passivating and improving crystalline silicon solar cells. Photovoltaic system technology compares the locations Stuttgart, Nicosia and Cairo, in order to investigate the effects of different materials, solar cell types, and climates on the annual energy yield of the grid-connected systems. Novel thin film photodetectors enable the quantification of e.g. heart attack, cancer, and inflammation markers in a mobile microsystem for so-called point-of-care testing which we develop in cooperation with several institutes of the Universities Tübingen and Stuttgart, and with the “Institut für Mikroelektronik” Stuttgart.
Gruppe Industrielle Solarzellen
Group Industrial Solar Cells

(Gruppenleiterin / Group Leader: Renate Zapf-Gottwick)

Our group “Industrial Solar Cells” is engaged in different research activities for higher efficiencies and less production costs of solar cells in industry oriented processes. Our stable “baseline” on a high efficiency level as a reference, shows that innovative add-on processes have still a great potential for boosting the efficiency. We work together with the other ipv-groups on add-on processes like the contacting of high ohmic emitters with and without laser-doped selective emitter, the fine-line screen printing of the front side metallization, the replacement of silver, which is a cost-intensive part in solar cell processing, by other materials and also the alternatives to the aluminium back side. The optimization of solar modules is also important. Here we are working on the decrease of optical losses by activating optical inactive parts of the module.
Gruppe Charakterisierung
Group Characterization

(Gruppenleiter / Group Leader: Markus Schubert)

The “Device Analysis” group deals with the characterization and simulation of semiconductor layers, solar cells and photovoltaic systems. The group makes use of measurement setups for the electrical and optical device characterization, e.g. lifetime measurements, current/voltage-characteristics, quantum efficiency, electro- and photoluminescence and measurement of spatially resolved short circuit current density. The process adjacent characterization monitors and evaluates the production steps of mono- and multicrystalline silicon solar cells. The group further develops novel concepts for photovoltaic efficiency enhancement. Scattering of light with so far only electrically active contacts and contact layers aims at the more efficient coupling of light into photovoltaic devices.
Silizium

einkristallines
mikrokristallines
nanokristallines
amorphes
Wissenschaftliche Beiträge
Scientific Contributions

Publikationen
Publications
Laser Edge Isolation Analysis on Si-Solar Cells

Author: A. Bertram
In collaboration with: J. R. Köhler

Different processes can be used for the disjunction of the solar cell emitter at the cell edge like plasma etching or wet chemical etching of the wafer edges [1]. The main disadvantages of these processes are that at least one additional process step has to be performed and a special and expensive recycling of the chemical waste is necessary. Laser edge isolation (LEI) does not produce chemical waste and allows a smooth integration into the solar cell process automation. For evaluating the LEI process, we investigate the following processing parameters: focus position \( f_p \), overlap \( O \) of the single laser pulses, and laser pulse energy density \( E_p \).

Figure 1 describes sample preparation and specific resistance measurements. In order to save wafer material for examining different LEI processing parameters, we use test structures of 1 cm length from a conventionally processed mono crystalline silicon cell. Laser edge isolation is performed between the contact fingers on the stripes using different processing parameters.

Figure 2 and 3 show the good correlation between the specific resistance measurements of the 1 cm test structures and 6\(^\circ\) solar cells processed with LEI. We conclude that a pulse to pulse overlap \( O = 80\% \) is necessary to achieve good isolation results over a
wide range of focus positions. Slightly better isolation results are achieved with \( O = 70\% \) and a focus position \(-300 \mu m < f_p < -400 \mu m\) below the wafer surface at the expense of a higher sensitivity on the exact focus position.

![Figure 2: Specific isolation resistance of LEI versus focus position -400 \mu m < f_p < +600 \mu m.](image)

![Figure 3: Parallel \( R_p \) values of mono-crystalline 6" silicon solar cell versus focus position \( f_p \).](image)

Table 1 shows microscope images of the LEI grooves together with \( R_p \) data. We conclude that not only a deep groove produces good isolation values but also a formation like a hillock.

<table>
<thead>
<tr>
<th>Focus position ( f_p )</th>
<th>Pulse overlap ( O = 70% )</th>
<th>Pulse overlap ( O = 80% )</th>
</tr>
</thead>
<tbody>
<tr>
<td>-400 \mu m</td>
<td>( R_p = 28.35 \text{k}\Omega \text{cm}^2 )</td>
<td>( R_p = 28.35 \text{k}\Omega \text{cm}^2 )</td>
</tr>
<tr>
<td>300 \mu m</td>
<td>( R_p = 28.35 \text{k}\Omega \text{cm}^2 )</td>
<td>( R_p = 28.35 \text{k}\Omega \text{cm}^2 )</td>
</tr>
</tbody>
</table>

References:

Contacting High Ohmic Emitters

Author: B. Bazer-Bachi
In collaboration with: M. Saueressig, G. Kulushich, and R. Zapf-Gottwick

The increase of the sheet resistance of the n-type emitter is one way to increase the efficiency of the solar cells [1]. In this case, the recombination losses in the emitter region are reduced, resulting in a higher collection probability of the minority carriers. However, a higher emitter sheet resistance leads to an increase of the contact resistance between the emitter and the screen-printed silver (Ag) paste.

Here we compare two screen-printed Ag-pastes on two different phosphorus doped emitters with sheet resistances $R_{\text{sheet},1} = 60 \ \Omega$/sq and $R_{\text{sheet},2} = 80 \ \Omega$/sq on monocristalline p-type wafers. Table 1 presents the average electrical parameters for 6" pseudo square Cz (Czochralski) solar cells, obtained on the two emitters, for our standard paste and our new paste.

Table 1: Average electrical parameters for solar cells with $R_{\text{sheet},1} = 60 \ \Omega$/sq and $R_{\text{sheet},2} = 80 \ \Omega$/sq. In each case, two silver pastes are tested: standard paste and new paste. The 80 $\Omega$/sq emitter and new paste show higher efficiencies.

<table>
<thead>
<tr>
<th>Emitter doping</th>
<th>Paste type</th>
<th>$J_{\text{sc}}$ (mA/cm$^2$)</th>
<th>$V_{\text{oc}}$ (mV)</th>
<th>FF (%)</th>
<th>$\eta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 $\Omega$/sq</td>
<td>Standard</td>
<td>36.5</td>
<td>623</td>
<td>76.9</td>
<td>17.5</td>
</tr>
<tr>
<td></td>
<td>New</td>
<td>36.6</td>
<td>628</td>
<td>78.8</td>
<td>18.1</td>
</tr>
<tr>
<td>80 $\Omega$/sq</td>
<td>Standard</td>
<td>37.1</td>
<td>626</td>
<td>76.6</td>
<td>17.6</td>
</tr>
<tr>
<td></td>
<td>New</td>
<td>37.1</td>
<td>630</td>
<td>78.3</td>
<td>18.3</td>
</tr>
</tbody>
</table>

The use of a higher emitter sheet resistance leads to an increase of the short circuit current density $J_{\text{sc}}$ and of the open circuit voltage $V_{\text{oc}}$ (Tab.1), either for both pastes. This enhancement is also noticed considering the internal quantum efficiency of the cells in Fig.1: a higher sheet resistance leads to a better response in the blue region.
However, with the 80 Ω/sq emitter, the fill factor $FF$ decreases mainly because of a series resistance increase due to lower contact quality.

Figure 1: Internal Quantum Efficiency (IQE) of two cells with emitters of $R_{ext} = 60, 80$ Ω/sq. Emitter with $R_{ext} = 80$ Ω/sq enables a higher blue response.

Comparing the effect of the paste type on the solar cell results for both emitters, all the I/V-parameters increase thanks to the new paste. The gain in $FF$ is explained by the higher capacity of the new paste to contact high ohmic emitters. Indeed in this case, we note a decrease of the series resistance. The $V_{oc}$ also increases, thanks to lower recombination losses. The new paste thus introduces less defects in the emitter and in the space charge region.

Decreasing of recombination losses with high ohmic emitter leads to an efficiency increase of 0.1 - 0.2 % absolute. Moreover, reducing the contact resistance between Ag paste and emitter with the use of the new paste enables an efficiency increase of 0.6 - 0.7 % absolute. Finally, coupling different emitter and different paste shows a maximum efficiency mean value of 18.3 %.

References:
[1] PV Technology Roadmap Forum, ICM Munich, Germany, 2010
Two Step Process for Laser Transferred Contacts

Author: E. Hoffmann
In collaboration with: T. C. Röder

Laser transferred contacts (LTC) offer a high efficiency fine-line front side metallization, reducing optical losses and utilizing low contact resistance $R_C < 1 \, \text{m} \Omega \text{cm}^2$. Our LTC process deposits a nickel seed layer through a SiN$_X$ anti-reflective coating (ARC) on the solar cell front side which is subsequently thickened by a nickel/copper plating step.

Figure 1a shows the one-step LTC process. A first laser pulse transfers evaporated nickel from a transparent substrate described in [1]. Following laser pulses overlap the area of preceding pulses and partly irradiate the nickel film on the substrate. Therefore, laser pulses fire already transferred nickel through the ARC and simultaneously trigger further nickel transfer. Figure 1b illustrates the two-step LTC process. During step 1 the laser beam transfers nickel without overlap and therefore without penetrating the SiN$_X$ surface. In the second step the laser beam irradiates the deposited nickel film again, using a lower pulse energy density $E_p$, allowing to control the penetration depth.

Figure 1:
a) Nickel transfer and contact formation in a single irradiation step.
b) Two irradiation steps allow the independent control of nickel transfer and contact formation.
Figure 2a shows the penetration depth on the cell surface, using the one- and two-step process, versus number of laser pulses. For both processes a single laser pulse transfers nickel without penetrating the SiNx. Only subsequent pulses lead to a penetration of the surface. For the one-step process already with a second pulse the penetration depth exceeds the emitter depth. Low energy laser pulses irradiate the sample during the second part of the two-step process without emitter penetration. Figure 2b displays penetration depth versus pulse energy density $E_P$. In the one-step process SiNx penetration is only detected for $E_P > E_{th,Ni} = 1.27 \text{ J/cm}^2$, as the nickel needs to be removed from glass, before penetrating SiNx. The curve corresponding to the two-step process shows the penetration depth of the second irradiation step. Penetration already commences for pulse energies $E_{th,SiNx} = 0.46 \text{ J/cm}^2$, penetrating only the ARC. With increasing pulse energy density the silicon is also penetrated. The two-step process allows us to contact the emitter through the ARC, without penetrating the emitter completely, which would short circuit the solar cell.

Figure 2:
(a) Lower laser pulse energy density reduces penetration depth. (b) Using the one-step process penetration depth always exceeds the emitter depth. The lower possible pulse energy density using the two-step process avoids complete emitter penetration.

References:
Numerical Simulation of Back-Contact Back-Junction Solar Cell

Author: G. Kulushich
In collaboration with: R. Zapf-Gottwick and J. H. Wemer

This work applies state of the art computer modelling to optimize the structure of laser-processed \textit{ipv} back-contact back-junction (BCBJ) c-Si solar cells. We employ Silvaco® Atlas software to investigate the internal quantum efficiency IQE of the cell with various front surface field (FSF) profiles.

Figure 1 illustrates the cross section of a BCBJ solar cell used for the 2D-numerical simulation. The cell with a thickness $d = 200 \, \mu m$ has an $n$-type base with resistivity $\rho = 1 \, \Omega cm$ and Shockley-Read-Hall lifetimes of holes $\tau_{SRH,p}$ and electrons $\tau_{SRH,e}$ being equal to $\tau_{SRH,p} = \tau_{SRH,e} = 2 \, ms$. A Gaussian $n^+$-type FSF and a dielectric layer on the front side passivate the front side. A Gaussian $n^{++}$-type back surface field (BSF) reduces the recombination rate at the back side of the base. A dielectric layer passivates the rear side of the cell. The recombination velocity $S_{n/e}$ at the metal/emitter contact equals the electron thermal velocity $v_{th,e} = 2.3 \times 10^7 \, cm/s$ in Si and the recombination velocity $S_{n/BSF}$ at the metal/BSF contact equals the hole thermal velocity $v_{th,h} = 1.6 \times 10^7 \, cm/s$ in Si.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Cross section of a BCBJ solar cell with $n^+$-type FSF, $n^{++}$-type laser doped BSF, and $p^{++}$-type laser doped boron emitter. Dielectric SiO$_2$ layers passivate front- and rear side. Pitch $p$ defines smallest repeating unit. Laser transferred contacts (LTC) to emitter and base build rear side contacts.}
\end{figure}
Figure 2a displays a strong influence of the front side recombination velocity \( S_{\text{FSF}} \) on IQE for the case of the simulated cell without any FSF. The IQE has highest values for the ideal case of \( S_{\text{FSF}} = 0 \) cm/s. However, the IQE strongly decreases for \( S_{\text{FSF}} = 103 \) cm/s and almost diminishes at \( S_{\text{FSF}} = 106 \) cm/s.

Figure 2b shows the dependence of IQE on the FSF-depth \( d_{\text{FSF}} \) for a surface concentration \( C_{\text{FSF}} = 10^{19} \) cm\(^{-3}\). We assume a front side recombination velocity \( S_{\text{FSF}} = 103 \) cm/s [1]. There is a negligible difference in the recombination losses for 50 nm \( \leq d_{\text{FSF}} \leq 300 \) nm. The IQE curve drops for \( d_{\text{FSF}} = 500 \) nm due to increased Auger recombination loss. Figure 2c illustrates the dependence of IQE on \( d_{\text{FSF}} \) for \( C_{\text{FSF}} = 2 \times 10^{20} \) cm\(^{-3}\) with SFSF = 105 cm/s [1]. The IQE drops for \( d_{\text{FSF}} = 300 \) nm and almost diminishes for \( d_{\text{FSF}} = 500 \) nm. The comparison of IQE in the case of a cell with FSF (Fig. 2b and c) and without FSF (Fig. 2a) demonstrates the passivation effect of the FSF. The FSF passivates the front surface by means of a field effect, rejecting the minority carrier holes away from the front surface. Thus, in the case of FSF with \( S_{\text{FSF}} \neq 0 \) cm/s (Fig. 2b and c) there is a trade-off between the passivation effect of the FSF and the Auger recombination due to the heavily doped FSF region.

![Figure 2](image)

**Figure 2:**
Simulated internal quantum efficiencies IQE of BCBJ solar cells with pitch size \( p = 3000 \) \( \mu \)m and emitter width \( w_{\text{emitter}} = 2000 \) \( \mu \)m: a) without front surface field and different \( S_{\text{FSF}} \), b) with FSF of \( C_{\text{FSF}} = 10^{19} \) cm\(^{-3}\) and different depth \( d_{\text{FSF}} \), and c) with FSF of \( C_{\text{FSF}} = 2 \times 10^{20} \) cm\(^{-3}\) and different depth \( d_{\text{FSF}} \).

**References:**

Metal Assisted Surface Texture for String Ribbon Solar Cells

Author: J. Cichoszewski
In collaboration with: M. Reuter and J. H. Werner

State of the art industrial solar cells utilize a surface texture to reduce front surface reflection for increased power conversion efficiency. Alkaline or acidic etching results in cost effective and reliable surface texturing for crystalline silicon wafers. The String Ribbon (SR) method grows silicon wafers directly from silicon melt, and, therefore requires no wafer sawing. Unfortunately, due to the absence of saw damage neither acidic nor alkaline etch solutions enable a satisfying texture on SR material.

This work presents metal assisted etching (MAE) as a surface texturing method for nonstandard silicon material, e.g. SR-wafers. Figures 1 a-c display SR-wafers during all three texturing steps. Firstly, palladium deposits on the silicon surface from aqueous PdCl₂ solution and acts as the catalyst for the following etching step. Secondly, an acidic solution creates a porous silicon layer. Finally, a potassium hydroxide solution polishes off the porous silicon and structures the surface anisotropically.

Figure 1:
(a) Flat SR surface with Pd nano-cluster deposited from aqueous PdCl₂ solution; b) SR surface after metal assisted etching in HF:HNO₃:H₂O solution for t = 35 s; (c) Textured SR surface after restructuring and porous silicon removal in KOH.

Figure 2 presents the wavelength dependent reflectance of SR-wafers and the influence of the MAE texture and antireflective coating. The effective reflectance $R_{eff}$ is calculated by weighting the reflec-
tance $R$ with the AM1.5 G solar spectrum. Compared to the flat wafer with $R_{\text{eff}} = 39.3\%$, the MAE texture significantly lowers the reflection in the entire wavelength regime to $R_{\text{eff}} = 22.7\%$. Similarly, the MAE textured surface with silicon nitride antireflective coating has a significantly lower effective reflectance $R_{\text{eff}} = 9.7\%$ than the un-textured one with $R_{\text{eff}} = 11.6\%$.

Table 1 presents electrical values of SR-solar cells with and without texture. Compared to the reference group, the considerably reduced reflectance of the MAE texture results in an increased short circuit current density $J_{\text{sc}}$ by $\Delta J_{\text{sc}} = +0.6 \text{ mA/cm}^2$. Overall, the MAE texture increases the mean solar cell efficiency $\eta$ by $\Delta \eta = 0.4 \%_{\text{abs}}$.

Table 1: Characteristics for MAE textured and un-textured SR solar cells: Short circuit current density $J_{\text{sc}}$, open circuit voltage $V_{\text{oc}}$, fill factor $FF$, and number # of cells.

<table>
<thead>
<tr>
<th></th>
<th>$J_{\text{sc}}$ [mA/cm$^2$]</th>
<th>$V_{\text{oc}}$ [mV]</th>
<th>$FF$ [%]</th>
<th>[%]</th>
<th># cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAE texture</td>
<td>$31.9 \pm 0.5$</td>
<td>$597.7 \pm 4$</td>
<td>$76.5 \pm 0.4$</td>
<td>$14.5 \pm 0.2$</td>
<td>8</td>
</tr>
<tr>
<td>best*</td>
<td>$32.0$</td>
<td>$599.1$</td>
<td>$76.7$</td>
<td>$14.7$</td>
<td>1</td>
</tr>
<tr>
<td>No texture</td>
<td>$31.0 \pm 0.6$</td>
<td>$602.4 \pm 5$</td>
<td>$75.8 \pm 0.7$</td>
<td>$14.1 \pm 0.4$</td>
<td>8</td>
</tr>
<tr>
<td>best*</td>
<td>$31.4$</td>
<td>$604.9$</td>
<td>$77.0$</td>
<td>$14.6$</td>
<td>1</td>
</tr>
</tbody>
</table>

*Independently confirmed by ISECaLabs, Freiburg, Germany

References:

μc-Si_{1-x}C_x:H Back Side Passivation for Industrial Solar Cells

Author: K. Carstens
In collaboration with: S. Miyajima, B. Bazer-Bachi and R. Zapf-Gottwick

We present a p-type μc-Si_{1-x}C_x:H passivation layer deposited by plasma enhanced chemical vapor deposition for industrial silicon solar cells.

Figure 1 shows the result of a PC1D-simulation with varying backside surface recombination velocity. The simulation uses a bulk-lifetime $t_{\text{bulk}} = 150 \mu$s. The solar cell efficiency does not increase for a backside surface recombination velocity $S_r$ lower than $S_r \approx 50 \text{ cm/s}$. Therefore, our target is to improve passivation from $S_r = 3000 \text{ cm/s}$ with an aluminum back surface-field to about $S_r = 50$ to 100 cm/s.

![Figure 1](image)

Figure 1:
PC1D-simulation: Efficiency increases with decreasing surface recombination velocity. Target is to replace the standard aluminum back-surface-field with surface recombination velocity $S_r = 3000 \text{ cm/s}$ by a backside concept with $S_r = 50$ to 100 cm/s. Further reduction of the surface recombination velocity does not improve efficiency anymore.

Figure 2a) shows the structure of the solar cell. We use a diffused POCl$_3$ emitter, passivated by a silicon nitride antireflective coating. On the backside, the standard aluminum back-surface-field is replaced by a conducting and passivating p-doped μc-Si$_{1-x}$C$_x$:H layer, similar to previously reported μc-Si$_{1-x}$O$_x$:H [1]. An evaporated aluminum layer supplies the electrical contact. A 10 x 10 cm$^2$ solar cell produced on float-zone p-type silicon resulted in an efficiency $\eta = 18 \%$ with open circuit
voltage $V_{OC} = 618 \text{ mV}$, short circuit current density $J_{SC} = 37.8 \text{ mA/cm}^2$ and fill factor of $FF = 77 \%$. A larger 15.6 x 15.6 cm$^2$ solar cell produced on industrial Czochralski p-type silicon resulted in an efficiency $h = 17.1 \%$ with open circuit voltage $V_{OC} = 616 \text{ mV}$, short circuit current density $J_{SC} = 36.6 \text{ mA/cm}^2$ and fill factor $FF = 75.7 \%$. The difference of the electrical parameters results from different bulk lifetimes $t_{bulk}$ of the silicon material. Aluminum gettering improves the bulk lifetime for Czochralski-growth silicon, but is not applied to this solar cell yet. Further optimization, e.g. gettering, will increase the bulk lifetime for improved efficiency.

Figure 2b) shows the quantum efficiency measurement of the large scale solar cell. The reduction of quantum efficiency in the short wavelength range from $\lambda = 400$ to 500 nm indicates a large surface recombination velocity at the front surface. This limits the open circuit voltage $V_{OC}$ and short circuit current density $J_{SC}$. First solar cells with p-type $\mu$-Si$_{1-x}$C$_x$:H layer as backside contact had a solar cell efficiency $\eta = 17.1 \%$ on 15.6 x 15.6 cm$^2$ cell area. Emitter optimization promises higher open circuit voltage and efficiency.

Figure 2: 
(a) Solar cell structure used in this study. The rear aluminum back-surface-field generally used for industrial solar cells is replaced by a p-type $\mu$-Si$_{1-x}$C$_x$:H conductive passivation layer and an evaporated thin aluminum contact.

(b) Quantum efficiency of a test cell: low IQE for $\lambda = 400$ to 500 nm shows the efficiency to be limited by the front side of the solar cell.

References:
Defect Formation in Silicon during Laser Irradiation

Author: K. Ohmer  
In collaboration with: Y. Weng, J. R. Köhler, H. P. Strunk, and J. H. Werner

This research focuses on the defect formation in silicon during the irradiation by a laser. If silicon is irradiated, the silicon melts and re-crystallizes epitaxially afterwards. Depending on the laser parameters, defect formation is observed. The development of defects is suppressed by using a laser beam focused to a line with only several microns of width. The maximal allowed line width $w$ depends on crystal orientation. If a (111)-oriented surface is irradiated, the line width, where no defects develop, is much smaller when compared to the irradiation of a (100)-oriented surface.

Figures 1a) and b) show transmission electron microscope (TEM) images of two samples irradiated with the same laser parameters but different surface orientations. Figure 1a) presents a plane view of an (100)-oriented crystal irradiated by a laser. No defects are observable within the semiconductor. The dark lines are bending contours and arise due to the furling of the thinned silicon. In contrast, Fig. 1b) displays a plane view of a crystal with a (111)-orientated surface.

![Figure 1](image_url)  

**Figure 1:** TEM-images of two samples. (a) (100)-orientation. (b) (111)-orientation. The laser parameters used to irradiate both samples are identical: $w = 16 \, \mu m$ and $E_{PL} = 3.7 \, J/cm^2$. Many defects are apparent for the (111)-orientation, whereas no defects are found for the (100)-oriented crystal.
Areas with a high defect concentration are apparent. Nevertheless, diffraction images show, that the re-crystallization process is epitaxial. Using TEM-imaging, we find a dislocation-free re-crystallized layer on (100)-oriented silicon, for a line width \( w \leq 15 \mu\text{m} \). For (111)-oriented surfaces the use of a line width \( w \leq 5.2 \mu\text{m} \) results in no observable defects.

Wafers with (100)-oriented surface irradiated with a circular laser focus of diameter \( D = 36 \mu\text{m} \) or larger show the formation of micro-cracks. The cracks in the centre region of the laser beam are already visible using an optical microscope. The depth of these cracks strongly depends on the pulse energy density \( E_p \). The higher \( E_p \) is, the deeper the cracks become. Due to the fragility caused by these cracks, only the border areas of the irradiated region can be analyzed by TEM. Figure 2 shows a TEM-image of such an area. Cracks are apparent, but no hints for dislocations or a non-epitaxial growth are found using TEM.

![Figure 2: TEM image of silicon with an (100)-oriented surface, irradiated with a laser beam focused to a circle having a pulse energy density \( E_{pc} = 1.5 \text{ J/cm}^2 \), a pulse duration \( t = 55 \text{ ns} \) and a diameter \( D = 130 \mu\text{m} \). A crack is apparent within the silicon.](image)

References:
White Grid Fingers Reduce Shading in Modules

Author: L. Hamann
In collaboration with: G. C. Gläser, L. Prönneke, and J. H. Werner

The short circuit current density $J_{sc}$ of crystalline silicon solar modules is reduced by several optical losses: i) shading by busbars and grid fingers, ii) reflection of light in the module glass and in the ethylene vinyl acetate EVA sealing foil, iii) absorption of light in the window layers. White painted grid fingers in a solar module reduce the optical width of the fingers leading to a gain in short circuit current density $\Delta J_{sc} = +0.6 \, \%_{rel}$. Incoming radiation is scattered at the white painted fingers instead of being partially absorbed at the metallic surface [1]. The scattered radiation is totally reflected at the glass air interface of the module and has another chance to reach the active cell area.

Figure 1 shows the principle of total internal reflection at the inner glass, air interface in a solar module. Reflected rays with a reflection angle $\beta > \Phi_{TIR} = 41.8^\circ$, with $\Phi_{TIR}$ being the critical angle of total internal reflection, are totally reflected and have another chance to reach active cell area. The patented [2] scattering effect on white paint is independent of the angle of incidence. Approximately 50 % of the incoming light on the finger area is reflected on active cell area. Reflection measurements characterize the reflection properties of different white paints in the range of 400 nm < $\lambda$ < 1200 nm. Not only a high reflectivity but also a good printability of the paint is necessary to get optimum results. In this work a second screen printing process prints the paint after the firing process. To avoid the paint drying in the screen during the printing process, we use a paint, which is cured with a lamp directly after the screen printing. Ten one cell mini-modules with white painted fingers show a measured overprint of less than 8 % on active cell area.
Figure 1: Principle of scattering at the white surface of the colored finger. a) Without coloring, the incoming rays are reflected with reflection angle $\beta < \Phi_{\text{TRI}}$, with $\Phi_{\text{TRI}}$ being the critical angle of total internal reflection. b) With coloring, the incoming ray is scattered lambertian. With a certain probability, the reflection angle $\beta$ is higher than the critical angle $\Phi_{\text{TRI}}$. Total internal reflection occurs.

Figure 2 shows the measured short circuit current densities, comparing reference modules with modules with white painted fingers. Reducing the optical width of the grid fingers due to white paint leads to a gain $\Delta J_{\text{SC}} = +0.25$ mA/cm$^2$ in short circuit current density which corresponds to a relative gain $\Delta J_{\text{SC}} = +0.6$ %rel. Calculating the measured gain without overprinting active cell area leads to a gain $\Delta J_{\text{SC}} = +0.85$ mA/cm$^2$ which corresponds to a simulated gain $\Delta J_{\text{SC}} = +0.9$ mA/cm$^2$.

Figure 2: Difference in short circuit current density measured with in-house current / voltage measurement. Solar modules with white painted grid fingers gain $\Delta J_{\text{SC}} = 0.25$ mA/cm$^2$ in short circuit current density compared to reference modules without white painted fingers. Neglecting the overprint on active cell area, the measured result confirms the simulation.

References:


High Resolution Full Area Simulation of Multicrystalline Solar Cells

Author: L. Stoica
In collaboration with: P. Gedeon

Industrial multicrystalline silicon solar cells display strong inhomogeneities in the local diode parameters. Our model enables a full area simulation of inhomogeneity effects while maintaining the resolution of the spatially resolved input data in areas with high local inhomogeneity.

Figure 1 illustrates the simulation. We use a voltage calibrated photoluminescence (PL) image as input data segmented into blocks of variable size. The block size depends on the local homogeneity being as small as a single pixel or as large as the finger grid spacing. Each block represents an elementary solar cell in the simulated circuit consisting of a diode \( (I_0, n) \), a parallel resistor \( (R_p) \) and a photo generated current source \( (I_{ph}) \). The emitter interconnects the blocks via its sheet resistance \( R_s \).

![Figure 1: Two dimensional model of the solar cell. Voltage calibrated PL measurement is segmented into elementary solar cells. Each element consists of a diode \((I_0, n)\), a parallel resistor \((R_p)\) and a photo generated current source \((I_{ph})\). The emitter interconnects the elements via its sheet resistance \(R_s\).](image)
The circuit simulator SPICE simulates the resulting network. Our segmentation reduces the number of nodes in the circuit from $10^6$ to $6 \times 10^4$, lowering the simulation time to less than 30 minutes for industrial string ribbon (SR) solar cells.

Figure 2 compares the spatially resolved simulation data with a PL measurement. The SR solar cell has a higher defect density at the long edges than in the center area. After cutting off the edge regions, the local diode voltage $V$ increases in the center part and decreases in the disconnected edge regions. The measured open circuit voltage $V_{oc}$ of the center part increases by $\Delta V_{oc} = +4.1$ mV. Our simulation is able to predict the local voltage distribution and the increase in $V_{oc}$ by $\Delta V_{oc} = +3.8$ mV.

![Figure 2:](image)

Figure 2: Comparison of local voltage measurements before (a, b) and after (c, d) edge removal. The cut off edges are placed near the remaining solar cell in the PL image (c). The open circuit voltage $Voc$ increases in the center since the generated current is no longer leached by the low lifetime edges, which become darker. Simulation (in b) reproduces (in d) the measured local voltage distribution (c) and the increase in $V_{oc}$ of the central part by $\Delta V_{oc}$.

References:

Laser Doped Boron Emitters for crystalline silicon solar cells

Author: M. Dahlinger
In collaboration with: S. J. Eisele, J. R. Köhler, and P. Lill

We present a novel laser doping process with sputtered sub nanometer thick boron (B) layers as a precursor, which allows easy tailoring of the doping profile [1].

Figure 1 shows the measured sheet resistance $\rho_s$ of samples with B-precursor layer thicknesses $d_B$ for $0.3 \, \text{nm} < d_B < 1 \, \text{nm}$ after irradiation with pulse energy densities $0.88 \, \text{J/cm}^2 \leq H \leq 1.79 \, \text{J/cm}^2$. The sheet resistance is $40 \, \Omega/\text{sq} < \rho_s < 400 \, \Omega/\text{sq}$. It decreases with increasing pulse energy density $H$ and increases with decreasing precursor layer thickness $d_B$. Hence, the precursor layer acts as a finite dopant source.

Figure 1: Sheet resistances $\rho_s$ measured by four point probe measurement of samples with different boron precursor layer thicknesses $d_B$ after irradiation with varying pulse energy densities. The precursor layer thickness $d_B$ limits the minimum achievable sheet resistance $\rho_s$. With increasing pulse energy density $H$, the sheet resistance $\rho_s$ decreases for all precursor layer thicknesses $d_B$.

Figure 2a) shows the emitter profiles corresponding to the emphasized points from the dashed curve in Fig. 1 measured by secondary ion mass spectrometry. The B-precursor layer thickness is $d_B = 0.6 \, \text{nm}$ and the pulse energy density is varied.
The emitter depth $z_E$ increases from $z_E \approx 100$ nm to $z_E \approx 500$ nm with increasing pulse energy density $H$. At the same time the maximum B-concentration $c_{B,\text{max}}$ and sheet resistance $\rho_s$ decrease.

**Figure 2:**
- a) Emitter depth $z_E$ increases with pulse energy density $H$, while maximum boron concentration and sheet resistance $\rho_s$ decrease.
- b) For constant pulse energy density $H$ emitter depth is $z_E \approx 500$ nm. Decreasing the precursor layer thickness $d_p$ leads to a decreased boron doping concentration $c_B$ and an increased sheet resistance $\rho_s$.

Figure 2b) shows SIMS profiles of the emphasized points in Fig. 1 at constant pulse energy density $H = 1.79 \text{ J/cm}^2$ but different B-precursor layers thicknesses $0.3 \text{ nm} < d_p < 1 \text{ nm}$. The maximum boron concentration decreases from $c_{B,\text{max}} = 1 \times 10^{20} \text{ cm}^{-3}$ to $c_{B,\text{max}} = 2 \times 10^{19} \text{ cm}^{-3}$ with decreasing precursor layer thickness $d_p$. To proof the high quality of the laser doped boron emitters, we determine the emitter saturation current density $J_{DE} = 34 \text{ fA/cm}^2$, which corresponds to an implied open circuit voltage $V_{OC,\text{limit}} = 710 \text{ mV}$ for an emitter sheet resistance $\rho_s = 111 \Omega/\text{sq}$. The low emitter saturation current density $J_{DE} = 34 \text{ fA/cm}^2$ and the solar cell efficiency $\eta = 16.3\%$ on 4 cm² cell area for the best cell from a first run, demonstrate the high potential of these laser doped boron emitters.

**References:**

Beam Profile Optimization for Laser Doped Selective Emitters

Author: P. Lill
In collaboration with: T. C. Röder, M. Dahlinger, and J. R. Köhler

The $\text{ipv}$ laser doping process [1] offers an elegant method to generate highly doped regions underneath the contact fingers in selective emitter solar cells. A laser beam melts the silicon surface to facilitate in-diffusion of dopant atoms into liquid silicon. Melting of silicon flattens the surface texture in the irradiated area and thus increases reflectivity of the processed areas. Good alignment of the metal fingers on the selective emitter ensures low contact resistance [2]. Wider selective emitters simplify the alignment, but increase front side reflection due to the eradicated texture in a larger area.

We evaluate the effective reflection and the contact resistance for different finger and selective emitter widths in dependence of the laser beam characteristics along the cross-section perpendicular to the scanning direction by means of a one-dimensional numerical model. Figure 1 presents a schematic view of the contact finger misalignment together with a sketch of the two laser beam profiles implemented in our model.

**Figure 1:**
The impact of laser beam profiles and the contact finger misalignment is evaluated along a cross-section perpendicular to the scanning direction of the laser. The selective emitter width is easily adjustable by the top-hat profile width ($w_{\text{SE}} = w_{\text{TH}}$). In case of a Gaussian beam profile, the Gaussian width $\sigma_y$ influences the slope of the decreasing profile flanks.
Figure 2 shows the calculated contact resistance and effective reflectance in dependence of the laser beam profile and of finger misalignment for constant finger width and laser pulse energy. The effective reflectance for the metal finger is $R_{\text{eff}} \approx 100\%$, thus the overall effective reflectance increases as the misalignment increases because irradiated area, formally covered by the metal finger, is exposed. The contact resistance rises for increasing misalignment, because the electrical contact between metal finger and un-irradiated, lower doped, regions is worse compared to the selective emitter. By tuning the Gaussian width $\sigma_y$, the performance of the Gaussian beam profiles is adjustable over a large range.

![Figure 2: Calculated contact resistance and effective reflectance of a top-hat and three different Gaussian laser beam profiles for constant laser pulse energy $E_p = 30 \, \mu J$ and constant metal finger width $w_F = 100 \, \mu m$ for a different extent of misalignment.](image)

References:


Phosphorus Out-Diffusion from Liquid Silicon

Author: S. J. Eisele
In collaboration with: J. R. Köhler, G. Bilger, M. Dahlinger

This contribution focuses on the complex physical mechanisms which occur during laser annealing and doping processes. An exact tailoring of emitter or back surface field dopant profiles requires numerical simulations, which take into account all relevant material properties and physical processes. Therefore we extend our numerical model [1] by applying out-diffusion of already incorporated dopant atoms. A comparison of experimental and simulation results allows us to determine the out-diffusion velocity of phosphorus atoms in liquid silicon for the first time.

Figure 1 presents the full area laser doping process. The shape of the laser beam offers a Gaussian profile in the short axis with a full width half maximum (FWHM) \( w = 5 \, \mu m \) and an \( l = 200 \, \mu m \) wide tophat profile in the long axis. Due to \( w \ll l \) the gradient of the laser power density in \( y \)-direction is significantly smaller than in \( x \)-direction. Therefore, the experimental situation permits to solve the heat transport equation

\[
\frac{\partial T(x,z,t)}{\partial t} = \frac{1}{c_p(T)\rho(T)} \left[ \nabla \{ \lambda(T) \nabla T(x,z,t) \} + \alpha(T)I(x,z,t) \right], \tag{1}
\]

and the diffusion equation

\[
\frac{\partial C(x,z,t)}{\partial t} = \nabla \{ D(T(x,z,t)) \nabla (C(x,z,t)) \} + Q(x,z,t) \tag{2}
\]

in two dimensions \( x \) and \( z \). In Eq. (1), \( T \) denotes the temperature, \( c_p \) the heat capacity, \( \rho \) the density of mass, \( \lambda \) the thermal conductivity, \( \alpha \) the absorption coefficient, and \( I \) the time dependent power density of the laser beam. In Eq. (2), \( C \) is the dopant atom concentration, \( D \) the diffusion constant, and \( Q \) is a doping source at the silicon surface, which describes the in-diffusion of dopant atoms through the interface between the precursor layer and the silicon.
Our numerical model solves equations (1) and (2) using a finite difference solver. We apply the model to determine the out-diffusion of phosphorus in liquid silicon. As there is no doping source on the silicon surface, we eliminate the doping source $Q$ from the diffusion equation. Instead of a doping source, we use the doping profile of the $\rho_S = 60 \, \Omega/\text{sq}$ furnace diffused emitter as starting point for the simulation. The assumption that the number of out-diffusing doping atoms per surface element and time $\partial N / \partial t$ is proportional to the concentration $C$ on the surface $C(x,0,t)$, leads to

$$\frac{\partial N}{\partial t} = D_{\text{out}} C(x,0,T)$$

(3)

The out-diffusion velocity $D_{\text{out}}$ with the unit $1/\text{cm}$ is comparable to the surface recombination velocity of charge carriers. The result of our numerical simulations is a temperature independent out-diffusion velocity of phosphorus atoms in liquid silicon of $D_{\text{out}} = 8 \, \text{cm/s}$ with an accuracy $\Delta D_{\text{out}} = \pm 1 \, \text{cm/s}$.

![Figure 1](image.png)

**Figure 1:**
Schema of the laser doping process. We use a line shaped laser beam with a Gaussian profile in the short axis and a top-hat profile in the long axis.

**References:**

Dynamic String Interconnection versus Parallel Connection in Partially Shaded Condition

Author: T. Wurster
In collaboration with: R. Merz and M. B. Schubert

Partial shading of one photovoltaic (PV) module in a PV string limits the common current of all modules of the string [1]. The activation of a bypass diode of an affected module significantly reduces the maximum power point (MPP) voltage of the string. The parallel connection of multiple strings forces the inverter to decide whether to operate all strings at the new reduced MPP voltage of this string, or, to force the affected string to the higher MPP voltage of the remaining ones. The two operating points lead to high mismatch losses [2] of the whole system which add upon the mere shading loss of the affected string. To avoid such mismatch losses, the Dynamic String Interconnection (DSI) [2, 3] enables independent MPP tracking of multiple PV strings.

Figure 1a shows the test system to compare the performance of the DSI and the standard parallel connection of photovoltaic strings. The switching cabinet toggles the four connected PV strings, each a series connection of five PV modules, between DSI and parallel interconnection on a daily basis. The inverter connected to the output of the switching cabinet feeds the generated power to the grid. A data logger measures the output power $P_{PV}$ of the respective interconnection and also the solar irradiation by a c-Si sensor to enable the calculation of the performance. The complete shading of one module of string S1, and thereby forcing the activation of its bypass diode, allows to compare the DSI and the parallel connection in partially shaded operation.

Figure 1b shows the relative difference $\Delta \eta$ in performance of the two interconnection schemes. The DSI gains an overall $\Delta \eta_{\text{mean}} = 2.1 \%$ rel. compared to the parallel connection, and it outperforms the parallel connection for irradiations $120 \text{ Wm}^{-2} < \Phi < 1000 \text{ Wm}^{-2}$, while it lags behind for $\Phi_{PV} < 120 \text{ Wm}^{-2}$ and $\Phi_{PV} > 1000 \text{ Wm}^{-2}$. 
These losses arise due to the unchangeable starting and control sequences of the inverter. The integration of the DSI into an inverter topology will overcome these problems and is under development right now.

Figure 1:
Test system and results. a) The switching cabinet toggles four PV strings $S_2$, each a series connection of five PV modules, between DSI and parallel modes on a daily basis. A sensor measures the solar irradiation and an inverter feeds the power $P_{PV}$ to the grid. b) The DSI yields a $\Delta \eta_{\text{mean}} = 2.1\%$ rel. better performance than the parallel connection. Interferences with the inverter control algorithm cause losses for very small and very high irradiation.

References:
Numerical Model for the Laser Transfer Process

Author: T. C. Röder
In collaboration with: J. R. Köhler

Our laser transferred contacts (LTC) achieve finger width \( w \leq 30 \mu m \) [1] resulting in less metal covered area compared to standard screen printed contacts. The LTC process uses a pulsed green laser to transfer nickel from a glass support and directly contact the emitter through the anti-reflection coating. The laser heats the nickel through the glass support. If the temperatures at the glass/nickel interface reaches \( T > 2200 \, ^\circ C \), the glass starts to evaporate. The resulting gas pressure transfers the nickel layer from the glass support to the solar cell.

We develop a numerical model, which describes the transfer process by calculating the temperature profile in the glass support and nickel layer as well as the resulting gas pressure \( P \). The model takes into account two transfer mechanisms: the transfer of (i) completely molten layers and (ii) partly molten layers.

Figure 1 presents the two transfer mechanisms. For completely molten nickel layers, the gas pressure creates a liquid nickel bubble. The nickel bubble bursts, if the gas pressure inside the bubble reaches its critical value \( p_{krit} = 8\sigma_{surf}b^{-1}\sin(0.5\alpha) \), which depends on the surface tension \( \sigma_{surf} \), the bubble width \( b \), and the aperture angle \( \alpha \) of the bubble. For thick nickel layers, the transfer process occurs before the nickel layer is completely molten. The gas pressure expands the solid part of the nickel layer, thus resulting in tensile stress \( \sigma_{tan} = PRd^{-1} \). Here, \( P \) stands for the pressure at the interface, \( R \) for the bubble radius, and \( d \) for the thickness of the solid part of the nickel layer. If the stress \( \sigma_{tan} \) reaches the critical value for nickel, the layer bursts and the nickel transfers to the solar cell.
Figure 2 shows the modelled threshold energies $E_{th}$ for our Nd:YAG as well as Nd:YVO$_4$ laser in comparison with experimental values for different nickel layer thicknesses $d_{Ni}$. The good agreement of modelled with experimental values demonstrate that the description of the transfer process by the two different transfer mechanisms is correct.

References:

SALT and PEPPER for Point-of-Care Diagnostics

Author: M. Sämann
In collaboration with: M. B. Schubert, D. Furn*, G. Proll*, G. Gauglitz*

Currently available Point-Of-Care-Testing (POCT) devices are limited by complex test formats and by transduction technologies unfavorable for automation. Among optical sensor technologies, the Reflectometric Interference Spectroscopy (RIFS) is particularly well suited for generating miniaturized, robust and disposable sensors. RIFS systems are not only ideal for diagnostic applications, but moreover address life-science analytics including biotechnology, food monitoring and safety. The direct test format avoids complex sample pre-treatment and the addition of costly reagents, emerging as an advantage over competing test systems.

The SALT & PEPPER projects [1] develop a handheld-sized prototype system for mobile measurements of already developed clinically relevant diagnostic assays. The system integrates miniaturized devices, like amorphous silicon based photodiodes as sensors, an ASIC chip that measures the photocurrent and communicates with an external computer, and a cartridge based fluidic system with a vibratory micropump [2].

Figure 1 shows the cartridge based integrated detection unit, combining a microfluidic system with an optical transducer, spectrally selective photodiodes and an ASIC chip on the printed circuit board.

Figure 2 displays C-reactive protein (CRP) detection on the developed assay with various CRP concentrations in serum. Monitoring the CRP in serum allows to diagnose inflammations after surgeries in real time.

* Institute of Physical Chemistry, University of Tübingen
Figure 1:
Integrated detection unit combining a cartridge based fluidic system with an optical transducer, spectrally selective photodiodes and an ASIC chip on the printed circuit board.

Figure 2:
Monitoring of C-reactive protein in serum allows real-time diagnosis of inflammations after surgeries.

References:
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In-Situ Series Connection for Thin Film Silicon Solar Modules

Author: S. Miyajima
In collaboration with: R. Merz and M. B. Schubert

Monolithic series connection is an important technology for thin film solar modules. Layer patterning using a laser scribing method is generally used for thin film silicon solar modules on glass or metal substrates to realize the monolithic series connection [1]. However, it is difficult to apply this method to flexible polymer substrates because of the remarkably higher interconnection losses caused by local heating the substrates [2]. An alternative method for the monolithic series connection is required to realize low-cost roll-to-roll flexible modules.

Figure 1 shows a concept of in-situ monolithic series connection (ISSC) for an amorphous silicon (a-Si:H) module [3]. The paired masking wires separate the front transparent conductive oxide (TCO) during the sputtering. After the TCO deposition, the first wire shift #1 locally masks the TCO during the subsequent plasma deposition of the active p, i, and n-type a-Si:H layers. The second wire shift #2 and subsequent deposition of a back contact (ZnO/Al stack) realize a series connection between the back contact and the front TCO.

An a-Si:H module using the ISSC technique on a glass substrate was fabricated to demonstrate the potential of this technique. Figure 2 presents the performance of the ISSC module. The dark current / voltage characteristics clearly shows the shunt free series connection by the ISSC technique. The module efficiency of 5.0 % is mainly limited by the cell optimization. The average efficiency of a-Si:H solar cells fabricated without wire shift was 6.4 %. Our standard process for a-Si:H cells on Asahi-U substrates yields an initial efficiency of about 9 %, indicating that further optimization of the a-Si:H cells on ZnO substrate enables us to make an ISSC module with an efficiency of 7 %.
Figure 1:
Concept of the in-situ monolithic series connection of a thin film silicon module using masking wires. First, the paired masking wires separate the TCO into neighboring stripes. The wire shift #1 masks the TCO against the deposition of the active semiconductor layers to form linear openings (perpendicular to the cross section drawn here). The wire shift #2 separates the metal back contact into stripes.

Figure 2:
I/V characteristics of an ISSC module with a size of 26.4 x 20.0 cm² on a glass substrate. The illuminated I/V curve was measured under real sunlight with a power density of 880 Wm⁻². The dark I/V curve clearly indicates no shunt leakage caused by ISSC.

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Spectral Dependent Annual Yield of Different Photovoltaic Technologies
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Arbeitsgemeinschaft
Cooperation Project

Das Solarzentrum Stuttgart ist eine Arbeitsgemein- 
schaft des Institut für Photovoltaik (ipv) und des 
Steinbeiszentrum Angewandte Photovoltaik (STZ- 
PV). Ziel der Arbeitsgemeinschaft ist, Grundlagen- 
forschung, angewandte Forschung und Umsetzung der 
Erkenntnisse der Forschung in die Anwendung und indu-
strielle Praxis noch enger zu verzahnen.

Das STZ-PV beschäftigt sich mit der industriellen Umsetzung 
verbesserter Produktionstechniken für industrielle Zellen aus kristalli-
nem Silizium, dem Bau von Messgeräten, der Anwendung von Photovoltaik 
in Entwicklungsländern, der Begutachtung von Photovoltaikfabriken und 
Beratungen.
Lehrveranstaltungen
Lectures

Promotionen
Ph. D. Theses

Masterarbeiten
Master Theses

Bachelorarbeiten
Bachelor Theses

Gäste & ausländische Stipendiaten
Guests
Bauelemente der Mikroelektronik (Bachelor, 1. Semester)
J. H. Werner
Energiebänder und Leitfähigkeit
Silizium - der Werkstoff der Mikroelektronik
Elektronen und Löcher in Halbleitern
Ströme in Halbleitern
Nichtgleichgewicht und Injektion
Elektrostatisik des pn-Übergangs
Ströme im pn-Übergang

Photovoltaik I (Bachelor, 4. Semester)
J. H. Werner
Was die Photovoltaik leisten kann
Der Photovoltaische Effekt: Solarzelle, Solarmodul, Solaranlage
Sonnenspektrum und Energieverbrauch in Deutschland
Maximaler Wirkungsgrad einer Solarzelle
Grundprinzip einer Solarzelle
Einsatzschaltbild der Solarzelle
Photovoltaik-Materialien und -Technologien
Modultechnik
Photovoltaische Systemtechnik
Erträge von Photovoltaiksystemen
Photovoltaik-Markt

Optoelectronic Devices and Circuits I (Bachelor, 6. Semester)
J. H. Werner
Basic physics
Thermal radiation
Coherence
Semiconductor basics
Excitation/recombination in semiconductors
Light emitting diodes
Semiconductor lasers
Glass fibers
Photodetectors
Photovoltaik II (Master, 1./3. Semester)
J. H. Werner
Technologie einkristalliner Zellen
Rekombinationsmechanismen
Theorie der maximalen Wirkungsgrade
Optimierungsstrategien
Zweite und Dritte Generation Photovoltaik

Solid State Electronics (Master, 1./3. Semester)
J. H. Werner
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

Laser and Light Sources (Master, 1./3. Semester)
J. H. Werner and J. R. Köhler
The Human Eye
Light and Color
Photometry
Incoherent Light Sources
Light Emitting Diodes
Lasers
Laser Processing
Praktische Übungen im Labor „Halbleitermesstechnik“
(Master, 2. / 4. Semester)
J. H. Werner und M. B. Schubert

Herstellverfahren von Halbleitern und dünnen Schichten
Elektrische Messtechniken für Minoritäten und Majoritäten
Optische Messtechnik
Strukturelle Messtechniken

Energiewandlung (Master, 2. / 4. Semester)
J. H. Werner

Grundlagen der Kernenergie
Thermodynamik
Direkte Nutzung der Sonnenenergie (Solarthermie, Photovoltaik)
Indirekte Nutzung der Sonnenenergie (Wasserkraft, Windenergie)
Chemische Wandlung und Speicherung elektrischer Energie

Wissenschaftliches Vortragen und Schreiben I (Wintersemester)
J. H. Werner

Kernbotschaften
Aufbau eines Vortrags
Standardfehler (Strukturaehler, Technikfehler, Fehler im Auftreten)
Praktische Schritte zum Vortrag
Selbst- und Fremdbeurteilung (mit Videoaufzeichnung)

Wissenschaftliches Vortragen und Schreiben II ( Sommersemester)
J. H. Werner

Kernbotschaften
Aufbau und Elemente einer Publikation
Bilder, Tabellen und Referenzen
Promotionen
Ph. D. Theses

Rainer Merz
*In-Situ* Series Connection and Maximum Power Point Tracking for Amorphous Silicon Solar Modules

Michael Reuter
Thin Crystalline Silicon Solar Cells
Masterarbeiten
Master Theses

Ricardo Alberti
Determination of the effective diffusion length of solar cells
from photo- and electroluminescence images

Marcel Berner
Winkelabhängige Charakterisierung von Texturen

Andreas Botej-Junca
Entwurf und Optimierung eines Solarladereglers

Kai Carstens
Der Einfluss von Dickenvariationen auf String Ribbon Solarzellen

Morris Dahlinger
Laserepitaxie von Germanium- und Silizium-Germanium-
Dünnschichten

Ahmed Garamoun
Gamma factor measurement to optimize a-Si:H films

Lars Hamann
Optische Moduloptimierung

Bodo Konrad
Laserinduzierte Kontaktierung von Siliziumsolarzellen:
Ein Zweistufenprozess

Hannes Meyer-Schönbohm
Entwicklung und optische Charakterisierung eines
flexiblen Photovoltaikmoduls auf Basis kristallinen Siliziums
Bachelorarbeiten
Bachelor Theses

**Stefan Bechler**
Organische Solarzellen

**Pawel Burski**
Messaufbau zum Ertragsvergleich zwischen dynamischer Strang-Verschaltung und herkömmlicher Parallelschaltung

**Iulia Dan**
Solarzellen mit bleifreier Aluminium-Rückseite

**Philipp Donn**
Entwicklung einer Antireflekschicht mit mangan-dotiertem Zinksulfid

**Tim Hummel**
Neuprogrammierung des Modulsonnensimulators

**Denis Kastner**
Feinlinien-Metallisierung von Solarzellen

**Felix Kurz**
Identifikation und Auswertung schneller zeitabhängiger Vorgänge in Photovoltaikanlagen

**Stefan Mönch**
Dynamische Strang-Verschaltung als Wechselrichter-Topologie

**Ann-Kathrin Müller**
Photovoltaisches Wasserpumpsystem für Afrika
Raphael Pfeil  
Aufbau einer Solartankstelle für E-Bikes am ipv

Fabian Rudnick  
Photolumineszenz siliziumreicher Oxidschichten

Mohamed Sabry  
Combined Module and String Maximum Power Point Tracking

Christian Sämann  
In-Situ Solarzellentexturierung bei der Laserdiffusion

Mohamed Taha  
Alternating Current Generation and Maximum Power Point Tracking with H-Bridge

Patrick Wagner  
Erzeugung einer sinusförmigen Wechselspannung

Benjamin Wild  
Impedanzmessung an großflächigen Solarzellen
Gäste & ausländische Stipendiaten

Guests

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Thomas Lenz
Universität Erlangen-Nürnberg

Mohamed Makhlouf
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Pontificia Universidade Católica de Minas Gerais, Brasilien

Mohamed Sabry
German University in Cairo, Ägypten

Mohamed Taha
German University in Cairo, Ägypten
Was sonst noch war ...
More than Science ...

Mitarbeiterliste
Staff Members

Lageplan
Location Map
Was sonst noch war ...
More than Science ...
**Girls’ Day**

**Gründung des Solarzentrums Stuttgart**

**1. Preis der Otto F. Scharff-Stiftung**

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**Girls’ Day**
On 14th April this year’s Girls’ Day took place. Under the guidance of Renate Zapf-Gottwick interested students obtained an insight view into our institute and about studying engineering.

**Formation of the “Solarzentrum Stuttgart”**
This summer the “Solarzentrum Stuttgart” was founded (www.solarzentrum-stuttgart.com). It is a cooperation project between the “Institute for Photovoltaics” (ipv) at the University of Stuttgart and the “Steinbeiszentrum Angewandte Photovoltaik”. The Steinbeiszentrum performs technology consulting for the production and characterization of industrial cells.

**First Award by the Otto F. Scharff-Foundation**
Bastian Zinßer with his dissertation on “Annual energy yields of different photovoltaic technologies in various climatic conditions” got the first prize by the Otto F. Scharff-Foundation. He received the award at a ceremony.
Tag der Wissenschaft

Umbenennung des Instituts

Science Day
On 2nd July our institute presented itself to the interested public and opened its doors. In addition to lab-tours and demonstrations of students self-made power converters, the children had the opportunity to construct a so-called “Grätzel-cell”.

Renaming of the Institute
Since the first of October and after over 60 years of history as “ipe”, the “Institute of Physical Electronics” was renamed into “Institute for photovoltaics” (ipv). The new name stands for a more direct association with the objectives and tasks of the institute. The research will be continued in the way as it was done during many successful years before.
1973 - 2011: Die Ära Bilger am ipe
Era Bilger at ipe
Turbo pumps and helicopters are only two of Gerhard Bilger's passions. Surface analyses, sputter tools, vacuum technology and electronics – the big advisor with the sharp tongue will only be a visitor from now.
### Mitarbeiterliste

#### Staff Members

<table>
<thead>
<tr>
<th>Name</th>
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<th>Arbeitsgebiet</th>
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