Back-contacted high-efficiency silicon solar cells – opportunities for low-cost metallization and cell interconnection

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ABSTRACT

This paper presents ISFH's recent developments and advances in the field of back-contacted silicon solar cells. The efficiency potential of back-contacted solar cells is very high; nevertheless, in industrial production, back-contacted solar cells are decidedly the minority. In the field of back-contacted solar cells, ISFH has developed several cell concepts and new processing techniques, such as laser ablation for silicon structuring, contact opening through passivation layers, and hole drilling for emitter-wrap-through (EWT) solar cells. The latest results are presented regarding ISFH's work on back-junction back-contacted solar cells and EWT solar cells, as well as on back-contacted solar cells employing an amorphous/crystalline silicon heterojunction. Also discussed are the advances in high-throughput evaporation of aluminium as a low-cost option for the metallization of back-contacted solar cells. Finally, a novel, silver-free cell interconnection technique is presented, which is based on the direct laser welding of a highly conductive, low-cost Al foil, as a cell interconnect, onto the rear side of back-contacted solar cells.

Introduction

In 1977, Lammert and Schwartz [1] proposed the concept of the interdigitated back-contact solar cell for use in concentrated sunlight; since then, many different designs of back-contacted silicon solar cells have been proposed and further developed, as summarized in a review article by Kerschaver and Beaucarne [2]. In high-volume production, back-contacted silicon solar cells have already achieved efficiencies of more than 22% [3]. In addition, SunPower have reported an energy conversion efficiency of 24.2% on an area of 155.1cm^2, thus proving the potential of this solar cell structure [4].

Besides the back-junction back-contact (BJBC) concept, the field of back-contacted solar cells also includes the emitter-wrap-through (EWT) structure [5,6] and the metal-wrap-through (MWT) technology [7]. While the EWT concept is currently not commercialized, possibilities for industrial-scale production were investigated by the former Advent Solar (now owned by AMAT), yielding efficiencies of up to 19.0% on boron-doped p-type Czochralski-grown silicon (Cz-Si) [8]. MWT solar cells, meanwhile, have achieved 19.7% on n-type Cz-Si [9] and 20.1% on B-doped p-type Cz-Si [10].

The fact that back-contacted solar cells provide the metallization for both electrical polarities at the rear side has the potential to simplify the cell interconnection process in module manufacturing. In the past, several processes have been developed specifically for the interconnection of back-contacted solar cells. MWT cells, for example, are glued with conductive adhesives to a conductive backsheet [11,12]. Typical conductive adhesives contain silver [12] and are therefore cost intensive. In other, much more advanced or explorative, concepts the front side of the cell is processed first, after which the cells are bonded to a glass substrate [13,14]. The rear side of the cells is subsequently processed, and finally the cells are interconnected either by low-temperature Ag paste [13] or by a combination of Ag/Al metallization and a transparent conductive oxide [14].

This paper summarizes recent results obtained by ISFH on back-contacted wafer solar cells, including BJBC and EWT, as well as the combination of the back-junction concept with amorphous/crystalline silicon (a-Si:H/c-Si) heterojunction (SHJ) technology. Each of these three concepts has distinct advantages. While the BJBC concept using, for example, a front-surface field (FSF) has the higher efficiency potential, EWT cells (emitter at the front) are known for their higher robustness with respect to variations in the front-surface passivation. Heterojunction technology, on the other hand, minimizes recombination by combining surface passivation with the process of contacting the solar cell.

In general, back-contacted solar cells require a high ratio of minority-carrier diffusion length *L* (within the bulk) to device thickness *W*, as well as exceptionally low values for the front-surface recombination velocity. The latter can be achieved either with direct passivation of the front side, by using a FSF, or with a (floating) emitter at the front side. In order to ensure high minority-carrier diffusion lengths within the bulk, P-doped, n-type Czochralski-grown silicon (Cz-Si) is used as base material.

> “ISFH developed two different technologies for the interconnection of Al-metallized solar cells.”

For the purpose of reducing the material cost, ISFH developed two different technologies for the interconnection of Al-metallized solar cells. Note that this metallization does not involve any masking steps, but instead a self-aligned separation of the contacts. Evaporation of Al has long been used for laboratory-type solar cells. However, this technique has so far not been implemented into industrial solar cell production on a large scale, in part due to the unavailability of a suitable cell interconnection technique for Al-metallized cells.

Two techniques for Al-based cell interconnection, as developed at ISFH, will therefore be presented in the last part of this paper. First, the deposition of solderable metal stacks, such as Al/Ni:V/Ag on Al-metallized stacks, is considered; importantly, these metal stacks can be deposited with the same equipment used to evaporate the Al. Second, a new interconnection technique recently developed at ISFH is presented, in which

the Al-metallized rear side of a solar cell is directly laser welded with an Al-layer to a transparent substrate (AMELI process).

Back-junction back-contact cells

For the fabrication of the BJBC solar cells, (100)-oriented phosphorus-doped 12.5×12.5cm^2 pseudo-square Cz-Si wafers were used, with a thickness of 200µm and a resistivity of 1.0Ωcm. A schematic cross section of the BJBC solar cells presented in this work is shown in Fig. 1. The front side of the cell is textured with random pyramids and passivated by plasma-enhanced chemical vapour deposited (PECVD) silicon nitride (SiN$_x$), which also acts as an anti-reflective coating. On the rear side, the boron-diffused p^+ emitter regions are interdigitated with phosphorus-diffused n^+ back-surface fields (BSFs) on two height levels. This structure is realized by laser ablation of silicon and an additional damage etching without any photolithographic patterning steps [15]. Both the emitter and the BSF are passivated with a thermally grown oxide layer (SiO$_2$). A picosecond laser is used for laser contact openings (LCO) by locally ablating the thermally grown SiO$_2$ [16].

The metallization of the cell is realized in a single mask-free vacuum evaporation process of aluminium and a thin layer of silicon oxide (SiO$_x$). The SiO$_x$ layer acts as an etching barrier in the next wet chemical aluminium etching step to achieve a self-aligned separation of the emitter and base regions. The separation of the contacts occurs at the vertical flanks of the laser-generated structure [17,18]. Note that the Al at the rear side of the cell is sufficient for module integration with ISFH's aluminium-based mechanical and electrical laser interconnection (AMELI) process, which will be discussed later.

Table 1 summarizes the measured parameters of such a BJBC baseline solar cell under standard testing conditions (25°C, 100mW/cm^2, AM 1.5G). These measurements were carried out in-house using a LOANA system from pv-tools, with the total area of the cell (155.1 cm^2) being illuminated. Table 1 also includes the performance of an optimized cell of the same size. For this optimized cell, an improved passivation layer was used for the rear side.

The baseline solar cell has an efficiency η = 20.7% and the optimized cell 21.4%. Both of these performances refer to the total wafer area, including all edges and busbars. The open-circuit voltages (V_{oc}) of 668mV and 683mV demonstrate effective passivation of the front and rear sides, respectively. The short-circuit current densities (J_{sc}) of 40.6mA/cm^2 and 40.8mA/cm^2 also confirm front-surface passivation and preservation of the high carrier lifetimes during the cell processing. The high current is further promoted by a large emitter coverage area as well as high rear-side reflection at the silicon/thermally grown SiO$_2$/aluminium. The fill factor (*FF*) losses are mainly due to a high series resistance (R_s) of 1.5Ωcm^2.

Simulations of the busbar regions [19] show that these regions have a significant impact on cell efficiency. These results were confirmed by measurements of cell performance with busbars excluded. Losses in the emitter busbar lead to a reduction in the fill factor, while losses in the base busbar reduce the short-circuit current density [3,19]. Therefore, a re-design of the cell layout – where one or both busbars are omitted – has the potential to realize a cell efficiency of over 21% for the baseline cell. For the optimized cell structures, a designated area efficiency of 22.4% on 133cm^2 has been determined.

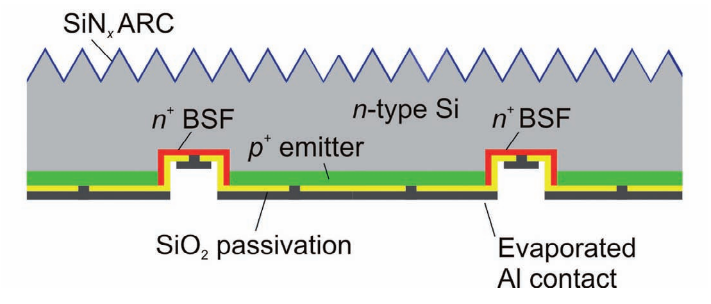


Figure 1. Cross section of the BJBC baseline cell presented in this work.

	A [cm^2]	η [%]	FF [%]	V_{oc} [mV]	J_{sc} [mA/cm^2]
Best baseline cell (Fig. 1)	155.1	20.7	76.4	668	40.6
Optimized process	155.1	21.4	76.9	683	40.8

Table 1. Cell parameters measured under standard testing conditions (STC) for a BJBC cell fabricated at ISFH.

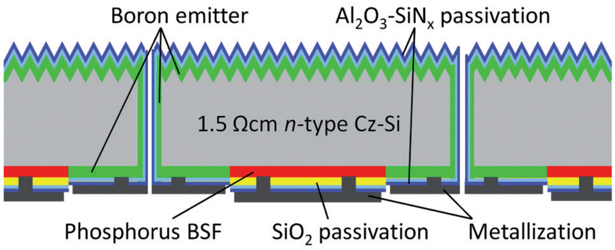


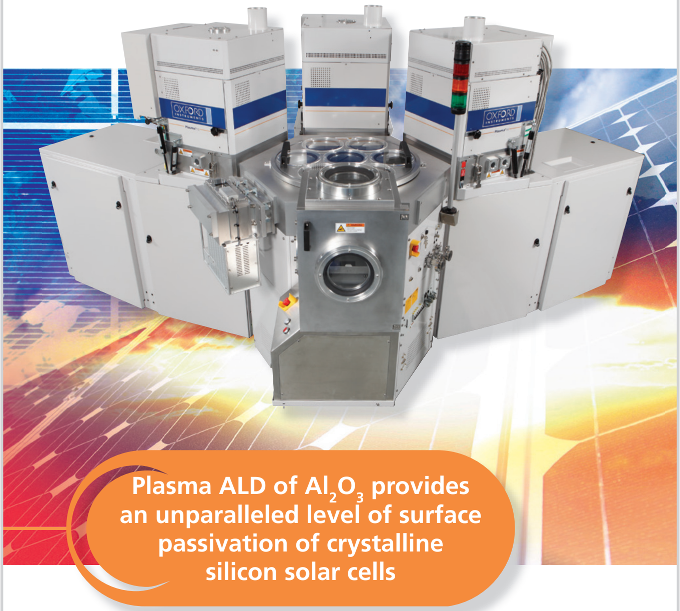
Figure 2. Schematic cross section of the EWT solar cell (adapted from Kiefer et al.).

High-efficiency emitter-wrap-through cells on n-type Cz-Si

For back-junction solar cells it is crucial to minimize the recombination at the front side, while EWT cells are far more tolerant. One possibility is the direct passivation of the base, as shown in Fig. 1; another, potentially more effective, way is the implementation of a FSF. However, when using a FSF it is imperative that both the control of the doping profile and the passivation are excellent. One way to overcome this issue is to use a front-side emitter instead of a FSF: the front-side emitter enhances the robustness of the cell structure to variations in front-surface passivation quality.

> “For back-junction solar cells it is crucial to minimize the recombination at the front side, while EWT cells are far more tolerant.”

As an alternative to a BJBC solar cell, a back-contacted solar cell can be realized using the concept of an EWT solar cell [6], connecting front and rear emitters by via holes. These via holes can be seen in the cross section of the EWT solar cells depicted in Fig. 2. Phosphorus-doped n-type silicon with a base resistivity of 1.5Ωcm was used. This design allows benefit to be gained from the combination of high lifetimes and high base conductivity. The layout of the rear side of our EWT cells has an interdigitated



	A [cm^2]	η [%]	FF [%]	V_{oc} [mV]	J_{sc} [mA/cm^2]
Small area	4	21.6	80.8	661	40.4
Large area	243.4	21.0	77.7	667	40.5

Table 2. Cell parameters measured under STC for n-type EWT solar cells fabricated at ISFH.

	A [cm^2]	η [%]	FF [%]	V_{oc} [mV]	J_{sc} [mA/cm^2]
IBC-SHJ (ISFH + HZB)	1	20.2	75.7	673.0	39.7
Both-side-contacted (ISFH)	4	19.8	74.4	695.0	38.3
Both-side-contacted (ISFH)	100	19.6	77.1	706.8	36.0

Table 3. Cell parameters for the IBC-SHJ solar cells fabricated in cooperation with HZB and for both-side-contacted SHJ solar cells fabricated at ISFH.

contact structure, similar to BJBC solar cells with a phosphorus-diffused BSF and boron-diffused p$^+$ emitter. The emitter is also formed on the front side and inside the via holes.

To achieve high open-circuit voltages with the solar cells, a thermally grown SiO_2 passivation layer was used for the phosphorus-doped base, along with an aluminium-oxide and silicon-nitride (Al_2O_3-SiN_x) passivation stack for the boron-diffused emitter surfaces, as depicted in Fig. 2. For contact formation, LCOs [16,20] were generated, and aluminium and a dielectric layer subsequently deposited on the rear side of the solar cell by vacuum deposition. The contact separation is realized with a combination of laser ablation and wet chemical etching.

With this cell structure, cell efficiencies of up to 21.6% for small-area solar cells (4cm^2, designated area without busbars) [21] were achieved. Table 2 summarizes the measured parameters of the cell, including a high EWT solar cell fill factor of 80.8%.

For the large-area 15.6×15.6cm^2 cells, full square Si wafers were used; in-house measurements were performed using the LOANA system. Table 2 shows the *I-V* parameters of the best large-area EWT solar cell with an efficiency of 21.0%, measured on the full area, including the busbars. The loss in fill factor compared to the small-area cell is mainly due to a higher series resistance. Longer contact fingers and extended minority and majority current paths in the busbar regions lead to this increased series resistance.

Heterojunction back-junction back-contact cells

The potential of BJBC solar cells can be further increased by combining it with amorphous/crystalline silicon (a-Si:H/c-Si) heterojunction (SHJ) [22–25] technology [26]. a-Si:H/c-Si heterojunction solar cells with contacts on the front and rear sides have already achieved high conversion efficiencies of up to 23.7% and open-circuit voltages of up to 745mV [27] because of the excellent surface passivation provided by thin a-Si. These solar cells, however, suffer from optical losses in the front a-Si:H layer and front transparent conductive oxide (TCO), as well as from contact shading of the metallization grid. These losses would not be present in a back-junction back-contact a-Si:H/c-Si heterojunction (BJBC-SHJ) solar cell, because no a-Si:H and TCO would be necessary at the front. A BJBC-SHJ solar cell thus promises excellent open-circuit voltages as well as high short-circuit current densities. Recently, very high efficiencies above 23% have been achieved with this approach [28].

Interdigitated back-contacted silicon heterojunction (IBC-SHJ) solar cells [29] were fabricated in cooperation with the Helmholtz Zentrum Berlin (HZB). Fig. 3 shows a schematic cross section of the IBC-SHJ solar cell; 3Ωcm n-type float-zone silicon was used as base material. The front side is textured with random pyramids and comprises a phosphorus-diffused n$^+$ FSF, with a sheet resistance of about 200Ω/sq. Passivation and anti-reflective coating are provided by a stack of thin thermal SiO_2 and PECVD SiN_x [30]. This surface preparation produces very little optical loss and provides stable and excellent front-surface passivation.

At the rear side, the gap between the n- and p-type regions is also passivated with a stack of thin thermal SiO_2 and PECVD SiN_x, resulting in very low surface recombination velocities [31]. The (i/p) a-Si:H emitter covers 60% of the rear side, the (i/n)a-Si:H BSF covers 28% and the gap 12%. The solar cells have a 1×1cm^2 active cell area and are fabricated using photolithography.

The *I-V* characteristics were measured using a Wacom 'WXS-156S-L2, AM1.5GMM' dual-source (tungsten and halogen lamp) sun simulator with class AAA characteristics at a temperature of 25.0±0.2°C. The intensity was adjusted using a calibration cell with front-side phosphorus diffusion. The aperture cell area of 1×1cm^2 was defined by a shadow mask and did not include the busbar areas.

Table 3 shows the results for the best IBC-SHJ solar cell, with an efficiency of 20.2±0.4%. The high short-circuit current density of 39.7mA/cm^2 demonstrates the effective light-trapping and high-passivation quality of the solar cell's front

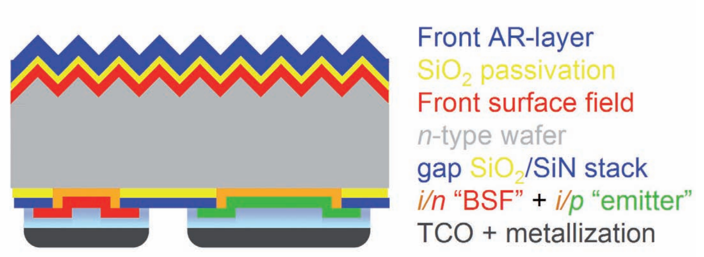


Figure 3. Schematic cross section of the IBC SHJ solar cell.

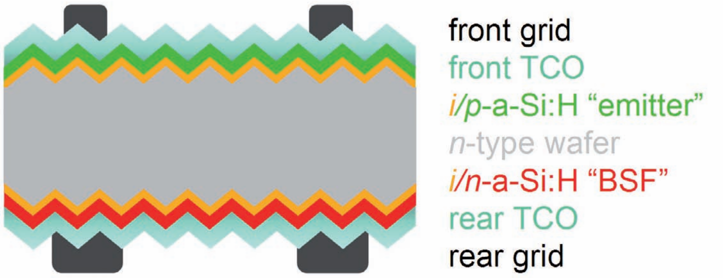


Figure 4. Schematic cross section of the both-side-contacted SHJ (HIT) solar cell.

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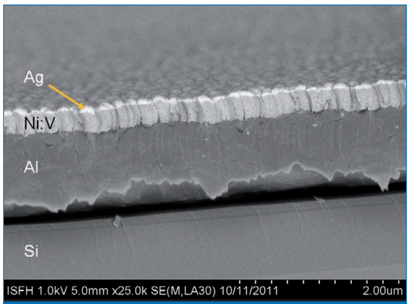

Figure 5. Cross-sectional SEM image of a metallization stack on a silicon wafer: 1µm evaporated Al (dark grey with breaking edge in the bottom of the layer), 250nm sputtered Ni:V (light grey) and 25nm sputtered Ag (white).

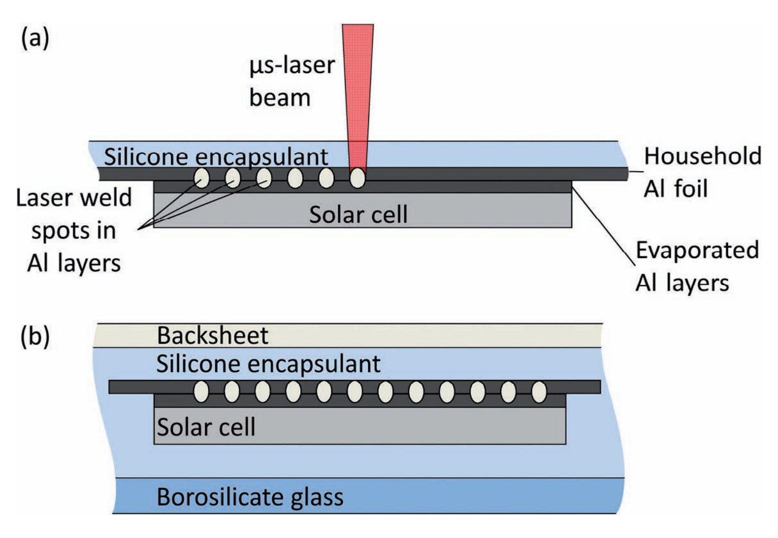

Figure 6. Schematics of (a) the laser weld process, and (b) the final lay-up of the module. (Adapted from [45].)

side. Although a relatively high voltage of 673mV was obtained, the potential of the solar cell concept is not exhausted.

In order to optimize the (i/p)a-Si:H emitter and (i/n)a-Si:H BSF stack, as well as the a-Si:H – TCO contact, a cell process for both-side-contacted SHJ solar cells was established at ISFH [32]. Fig. 4 shows a schematic cross section of one of these cells, which has a similar structure to the heterojunction with intrinsic thin layer (HIT) solar cell pioneered by Sanyo [22,27]. This relatively simple cell process allows a wide range of process parameter variations to be investigated without having to fabricate the complex IBC-SHJ solar cell structures. The metallization can be performed by aluminium evaporation or low-temperature, silver (Ag) screen printing. Table 3 shows the results for the best fully screen-printed 2.5×2.5cm^2 and 10×10cm^2 SHJ solar cells. *I–V* measurements were performed with a LOANA system from pv-tools.

Aluminium as contact material

A common step in producing all ISFH's solar cells is the evaporation of aluminium for the contact formation. This process has long been known as a laboratory technique for high-efficiency silicon solar cells [15]. With the exception of Schott Solar [33] and BP Solar [34], it has so far not been implemented into production lines on a large scale, even though the metal evaporation process is a well-known process from the coating industry. It is used on an industrial scale for various applications, for example to create protection layers in potato-crisp bags. Unfortunately, both the solar cell production lines have now closed down.

In recent years, however, high-throughput in-line evaporation systems have been investigated with regard to their applicability in silicon solar cell fabrication, and promising results have been obtained [35,36]. These systems (Applied Materials ATON500/ATON1600) allow a throughput of over 3000 wafers/h, with a flexible configuration of evaporation or sputter units. This enables a sequential deposition of different metals to create metal layer stacks without breaking the vacuum.

Evaporation of aluminium for contact formation on silicon solar cells offers distinct advantages over the standard metallization process (i.e. screen printing), such as the potential to reduce material costs, a higher throughput, lower process temperatures (and therefore less stress for the produced cells), a lower contact resistance (of the order of $10^{-3}\Omega cm^2$ [37]) between wafer and metal, and, most importantly, higher solar cell efficiencies (21.8% so far [38]).

The cost reductions arise because the need for expensive, potentially silver-containing, pastes is eliminated, and the amount of aluminium used is about 10% less than that currently required [36,39]. The process temperature depends on the deposition rate and the velocity of the carrier system transporting the wafer [39]. With the standard parameters, the deposition temperature is below 300°C, which results in wafer bows lower than 1mm on a standard 15.6cm wafer. However, it is also possible to form an Al-p$^+$ BSF, which reduces the surface recombination velocity (SRV) if a deposition temperature is chosen that is sufficiently high [40].

Module integration with evaporated aluminium

In general, crystalline silicon solar cells are interconnected by soldering. Unfortunately, aluminium is not directly solderable owing to the formation of a stable native oxide. In screen-printed both-side-contacted solar cells, soldering pads made from silver-containing pastes are used to ensure solderability, which is a significant cost distribution in module production.

> "Evaporation of aluminium for contact formation on silicon solar cells offers distinct advantages over the standard metallization process."

The solderability of an evaporated aluminium layer can, however, be achieved by depositing a metal stack of, for example, Al/Ni:V/Ag, as shown in Fig. 5. This can be done without breaking the vacuum. The silver capping layer in this stack has a thickness of only 25nm, leading to a silver consumption of approximately 6mg per 15.6×15.6cm^2 wafer, which is a significant reduction compared to the 50–90mg/wafer that is required in standard rear-side screen-printing processes [41].

Positive results on solderability and long-term stability tests of this metal stack on solar cells have recently been published; in these tests, the peel force for a solder joint on solar cells was investigated after thermal treatment between 80 and 150°C for up to 720h. In every peel test, the peel

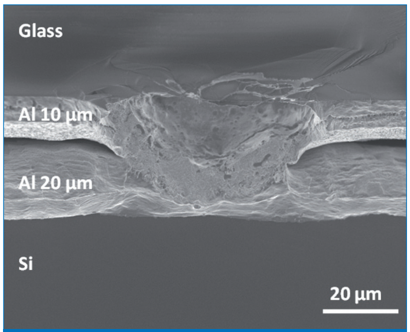

Figure 7. Cross-sectional SEM image of a laser weld spot of a sample with a 20µm-thick Al layer on the Si wafer, and a 10µm-thick Al layer on the glass substrate.

	A [cm^2]	η [%]	FF [%]	V_{oc} [mV]	I_{sc} [mA]
Cell 1	34.4	20.4	78.3	663	1350
Cell 2	34.4	20.8	78.5	666	1368
Cell 3	34.4	20.7	78.1	666	1372
Cell 4	34.4	20.2	77.5	664	1349
Cell 5	34.4	20.7	77.8	666	1377
Module	172	20.4	78.2	3326	1348
Module laminated	172	19.3	78.3	3320	1275

Table 4. Module parameters measured under standard conditions. The given area *A* is either the total area of a cell or the designated area of a module (area of the five cells only). (Adapted from [45].)

force exceeded the minimum peel force (defined in DIN EN 50461 to be 1N/mm) by a factor of more than four. From the analysis of inter-metallic compound growth at the solder/Ni:V-interface, it was possible to derive a required Ni:V layer thickness of less than 200nm for a lifetime of 25 years under realistic conditions [42].

A suitable way to solder back-contacted solar cells, using the specific advantage of having both contacts accessible on the same side, is the ATLAS (on-laminate laser soldering) process [43]. Here, the soldering process takes place after the cells have been positioned on the module glass and encapsulant, making further handling steps with unsupported fragile strings unnecessary.

An interconnection technique that omits silver completely was recently developed at ISFH. The so-called aluminium-based mechanical and electrical laser interconnection, or AMELI, process [44,45] forms laser weld spots between the Al-metallized rear side of a solar cell and an Al layer on a transparent substrate. Fig. 6 shows the schematics of the process using a silicone encapsulant as transparent substrate carrying a 10µm-thick Al foil. A pulsed laser beam is focused through the transparent substrate into the interface between the Al layer on the substrate and the cell metallization; as a result, the Al layers melt and fuse, as shown in Fig. 7.

The laser welding is performed using a Rofin StarCut Disc 100ICQ laser source. The laser pulses have a pulse duration of 1µs at a wavelength of 1030nm. The laser spot welds are formed by single laser pulses with a pulse energy of 2.3mJ. After the laser welding, the solar cells are interconnected via the Al foil, and the resultant module is then ready for final lamination.

The laser weld spots used for interconnection are characterized by the following properties [45]:

- Strong mechanical interconnection, resulting in a perpendicular tear-off stress of 380kPa after lamination of the stack.
- Low contact resistance ρ_c of less than 1×10^{-2}mΩcm^2 for a contact area of 420×940µm^2 with a welded area fraction covered by weld spots of 20%.
- Degradation of less than 3% of the contact resistance during accelerated aging experiments (300 humidity-freeze cycles, from -40°C to +85°C at 85% rel. humidity).

A proof-of-concept module was fabricated using 12.5×12.5cm^2 BJBC solar cells, which were laser cut into stripes of width 2.75cm. The cell parameters of five of these cells (cells 1 to 5) are given in Table 4. The cell stripes were subsequently interconnected in series using the AMELI process.

The module on the transparent substrate was measured after the laser interconnection and before lamination ('Module' in Table 4). For this in-house measurement, a module flasher (Halm) with a flash duration of 13ms was used. After lamination with a white backsheet and a borosilicate front glass (see Fig. 6(b)), the module was measured once again ('Module laminated'). Note that a shadow mask was used for the *I-V* measurements of the module: this limited

the illuminated area to the cell area.

The sum of the open-circuit voltages V_{oc} of the solar cells before welding was 3325mV, while the open-circuit voltage of the module before lamination was 3326mV. In addition, neither the fill factor FF nor the short-circuit current I_{sc} changes after laser welding, resulting in a module efficiency η of 20.4% (before lamination). It is thus concluded that the cell interconnection process does not induce any appreciable damage and that the Al weld has a very low contact resistance.

After lamination the efficiency decreases to 19.3% due to reflection and absorption in the front glass and the encapsulant, which notably decreases the short-circuit current. Modules fabricated by this interconnection process have shown to be stable under accelerated aging [46].

> "All of these cell structures have the potential for realizing efficiencies well above 22%."

Conclusions

An overview of back-contacted solar cells developed at ISFH has been presented, namely BJBC, EWT and IBC-SHJ. All of these cell structures have the potential for realizing efficiencies well above 22%, with a record efficiency of 24.2% having been achieved by SunPower in the case of BJBC cells [4].

All the back-contacted solar cells (BJBC, EWT and IBC-SHJ) at ISFH were metallized with evaporated aluminium, a method that offers very low material consumption cost. However, the practical utilization of Al-metallized cells requires novel cell interconnection techniques. Two processes for interconnecting solar cells with evaporated Al metallization were therefore presented: 1) the deposition of an additional metal stack using the same in-line system, such as Al/Ni:V/Ag, and subsequent soldering; and 2) direct laser welding of the Al on the solar cell rear side with an Al-layer on a transparent substrate (AMELI process). Both significantly reduce the silver usage per cell compared to state-of-the-art screen printing, while allowing the transfer of the solar cell results to the module level.

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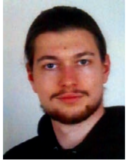

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