Metallization techniques and interconnection schemes for high-efficiency silicon heterojunction PV

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Market Watch
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Materials
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ABSTRACT

The major cell and module producers are focusing on silicon heterojunction technology as potentially the next generation of crystalline PV for mass production, since it has already demonstrated high energy conversion efficiency, easy integration in a bifacial module, low temperature coefficient and simplicity of manufacture. Because of the different cell architecture and materials involved in these solar cells, specific metallization and interconnection processes must be used. This paper discusses these processes, and in particular investigates the evolution of low-temperature-cured silver paste that has occurred in the market, as well as the impressive reduction in the specific bulk resistivity achieved in this area. The interconnection scheme used during module manufacturing strongly influences the requirement imposed on the solar cell metallization. In this respect, it is shown how significant silver saving can be achieved by using a combination of multiwire interconnection and fine-line screen-printing. For more specific interconnections requiring metallization with longer fingers, copper plating can be applied, resulting in a highly conductive metallization grid. Finally, the discussion will turn to how the metallization and interconnection techniques can be adapted to back-contacted silicon heterojunction solar cells.

Introduction

Since the first demonstration by Sanyo in the 90s of crystalline silicon heterojunction (SHJ) solar cells with already promising energy conversion efficiencies above 18% [1], this device architecture has experienced an extraordinary history of development, embodying outstanding scientific findings and efficiency records [2,3]. In particular, a significant breakthrough occurred in 2014, when Panasonic achieved a 25.6% cell efficiency with an interdigitated back-contact silicon heterojunction (IBC-SHJ) cell, which became the highest efficiency ever recorded for any crystalline silicon solar cell [4]. Even more recently, this quest for ultra-high efficiency has further intensified and led to efficiencies of 25.1% for a two-side-contacted SHJ [5] and 26.7% for an IBC architecture, which is the current world record for a crystalline silicon solar cell [6,7]. Industrially, there have also been impressive achievements, with the commercialization of high-efficiency SHJ-based solar modules [8], and the availability of production tools capable of manufacturing high-efficiency SHJ at an industrial throughput [9]. Of note is the AMPERE European

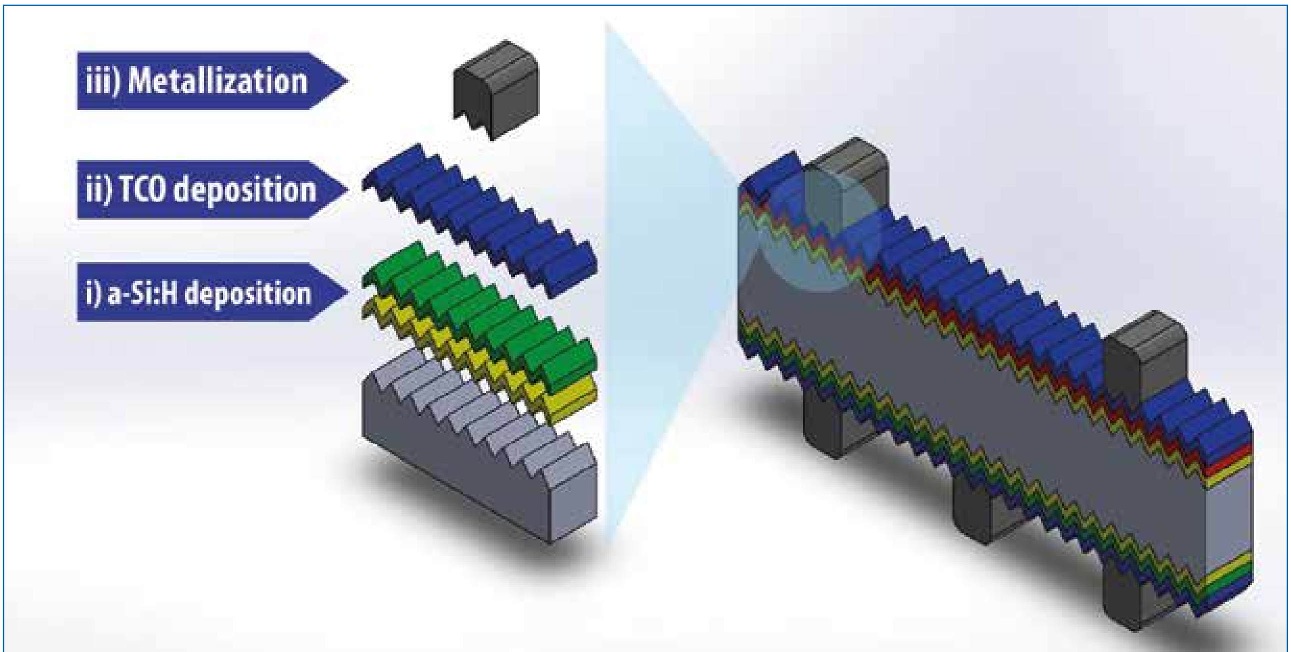


Figure 1. Manufacturing steps and schematic cross section of a finished bifacial silicon heterojunction solar cell.

initiative for setting up an innovative full-scale automated production line for SHJ cells and modules [10].

A key element in explaining the popularity of SHJ devices is their astonishingly simple architecture, and therefore the low number of process steps involved in their manufacture. Fig. 1 highlights this simplicity, whereby the textured silicon wafer is first coated with intrinsic and doped amorphous silicon to ensure excellent surface passivation (which is perfectly suited to the use of thin wafers), as well as to promote an efficient charge-carrier separation. This is followed by the deposition of transparent conductive oxide (TCO) layers, acting as both an antireflection coating and a conductive electrode to extract and laterally conduct the electrical current. In a final step, these electrodes are further reinforced by means of a metallization process, such as the screen printing of a silver paste [2]. In addition to the straightforwardness of their manufacture, SHJ cells also offer important advantages when deployed in PV installations: not only are they intrinsically made with a bifacial architecture, but they also feature a temperature coefficient in the range -0.23 to -0.3%/°C [11,12]. Furthermore, SHJ cells can be used in high-efficiency devices, such as tandems [13].

> “Specific low-temperature-cured silver pastes must be used for SHJ solar cells.”

A consequence of the significantly different cell architecture, and of the use of hydrogenated amorphous silicon, is a limitation of the maximum temperature acceptable for metallization, typically around 200°C. This clearly prohibits the use of silver metallization pastes used for homojunction devices, which are typically sintered around 800°C [2]. Therefore, specific low-temperature-cured silver pastes must be used for SHJ solar cells, with the inherent drawback of being around two to three times more resistive than their high-temperature counterparts; this has a considerable impact on the entire metallization and interconnection techniques used for cell and module manufacturing [14]. This paper will discuss how that limitation is circumvented with the recent developments made in SHJ metallization and module integration; it will also show how the appropriate metallization design and the cell interconnection scheme can be chosen.

Link between metallization techniques, grid design and interconnection scheme

The choice of the metallization technique is closely linked to the interconnection scheme used during module manufacturing, and vice versa; this consequently affects the design of the metallization grid. A key parameter of the grid design is the finger length, defined here as the maximum distance that the electricity has to flow along the finger (i.e. half the busbar-to-busbar distance in a standard H-pattern).

Fig. 2 shows an estimation of the power loss induced by a metallization grid for different line resistivities and different finger lengths (this includes the electrical power losses occurring in the TCO and the fingers and the shadowing of the fingers; busbars are not taken into account here). For each condition, an optimization of the number of fingers is carried out on the assumption of a constant TCO sheet resistance of 100Ω/sq. and a finger width of 50µm. The finger length is expressed in relation to different grid designs, ranging from an H-pattern with two busbars (finger length of 3.9cm) to the ultimate multiwire approach, in which the finger length is reduced to values below 10mm [15,16]. The different line resistivities are

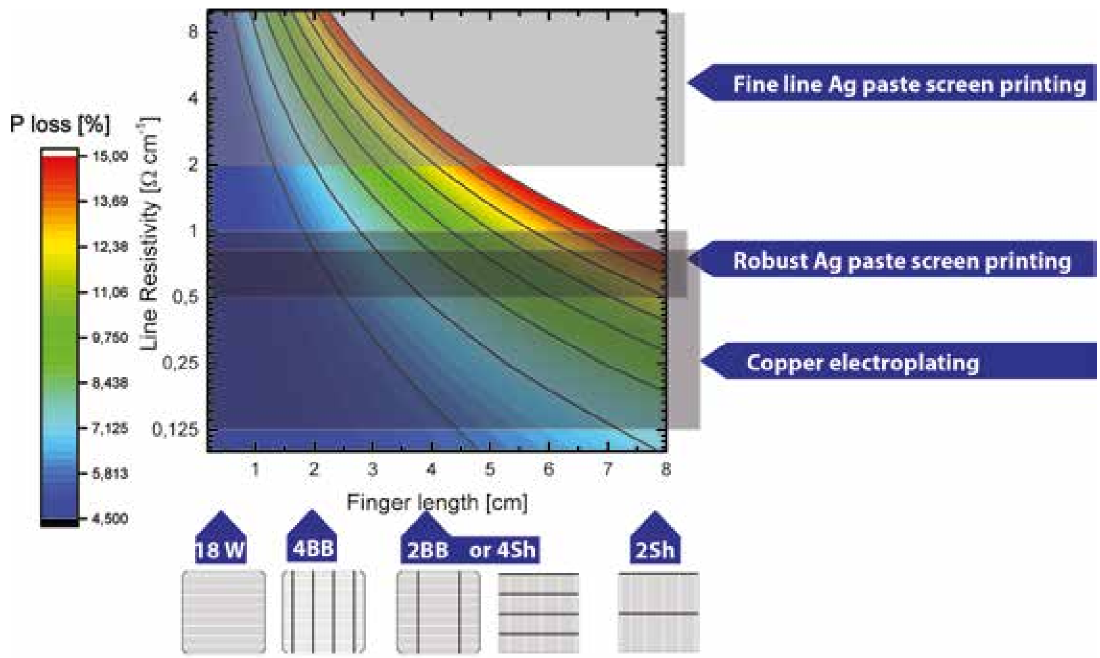


Figure 2. Estimation of optical and electrical power losses induced by a metallization grid, as a function of line resistivity and finger length. Examples of interconnection schemes are given for 18 wires (18W), two or four busbars (2BB or 4BB), and shingled-cell connection with two or four subcells (2Sh or 4Sh).

Cell Processing

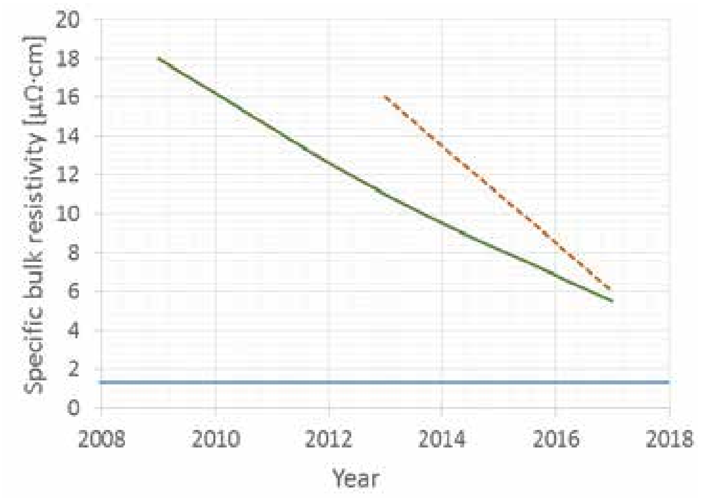


Figure 3. Evolution of the specific bulk resistivity of low-curing-temperature silver paste compared with pure silver (horizontal line). The continuous line represents the paste after 30min curing at 200°C, while the dashed line indicates the paste after curing for 30min at 180°C (data courtesy of Namics Corporation).

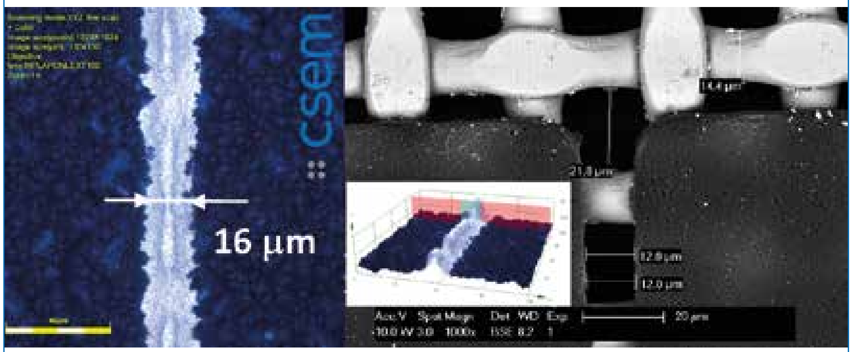
illustrated here by three metallization techniques: 1) fine-line silver paste screen printing; 2) 'robust' silver paste screen printing; and 3) copper electroplating.

From Fig. 2, the L^2 dependency of the power loss occurring in the finger can be identified, which shows clearly how the line resistivity constraint can be relaxed when switching from the busbar approach to the multiwire approach. In contrast, when fingers must be kept long, a different approach is necessary in order to achieve very low values of line resistivity. A good example is the shingled-cell approach, where cells are cut and directly interconnected to each other by overlapping them [17]. In this case, the number of subcells has to be ideally kept as low as possible in order to minimize the losses caused by the laser cutting, to avoid the handling of a large number of subcells and to reduce the lost area induced by the overlapping. As an example, if a four-subcell cut is considered, the finger length is equivalent to a two-busbar approach, which therefore implies that the line resistivity is to be kept at least below 1Ω/cm. In the following sections, different metallization techniques will be investigated, as well as adapted interconnections schemes.

Low curing-temperature silver paste and screen-printing technique

Within the last couple of years, the choice of low-curing-temperature silver paste dedicated to SHJ solar cells has changed drastically. Prior to that, high-performance low-temperature silver pastes were highly sensitive to their storage conditions, and their processing necessarily implied long curing times and temperatures above 200°C. In this respect, the curing had a significant impact on the cell precursor, resulting in a trade-off between the precursor performance and paste resistivity. Thanks to the developments made with these products during the last decade, the pastes can today be stored at ambient temperature or in a standard fridge, which greatly simplifies their storage and their shipment, allowing important reductions in cost. Regarding the curing, this step can now be done much faster and with an infrared furnace, which reduces both the thermal budget of the cell and the furnace footprint in the production environment. Certain pastes now obtain their optimal bulk resistivity after just a few minutes at only 150°C. The paste cost per weight is aligned to the silver price and is now in the same range compared to high temperature silver pastes. However due to their higher specific bulk resistivity, this implies using more low temperature silver paste. Thanks to improvements in the silver filler, composed of a multimodal distribution of flakes and particles [18], the best bulk resistivity has dropped from 18µΩ·cm back in 2009 to 5.5µΩ·cm today, as shown in Fig. 3. Some prototype pastes have even obtained values below 5µΩ·cm, which is only about three times the bulk resistivity of pure silver (1.58µΩ·cm). The printability of these products has improved significantly, leading to less paste spreading on the finger sides; this has meant a reduction in optical shadowing and an improvement in line conductivity, as smoother fingers can be obtained with the same amount of silver. As a consequence of these printability improvements, screen openings as small as 30µm and 20µm can be used in pilot production and in R&D respectively [19–21].

A record print of a line width of just 16µm on a textured wafer coated with ITO has been demonstrated by using a special mesh with zero-angle orientation and a screen opening of only 12µm, as shown in Fig. 4 [22]. High paste reflectivity and a triangular finger shape are preferred in order to reduce the effective finger shadowing on the module by 50 or 60% [23]. Finally, the range of products has increased, with specific pastes dedicated to ribbon interconnection, multiwire interconnection and busbar printing [24,25].



Source: CSEM

Figure 4. Optical image (left) and 3D image (inset) of a screen-printed line on a textured wafer coated with ITO, and SEM image (right) of the screen mesh and opening.

Credit: Meyer Burger

Figure 5. Busbarless cells and GridTouch measurement, the SWCT concept and the bifacial record module. The metallization and interconnection costs are reduced to a minimum level, while maintaining maximum product reliability. Courtesy of Meyer Burger.

Ribbon interconnection

Initially, SHJ solar cells used the same interconnection scheme as standard diffused cells, and were metallized using a busbar design and interconnected by soldered ribbons. However, for reliable soldering on low-temperature-cured silver paste, a minimum thickness of about 20µm at the busbar is necessary in order to avoid silver leaching. For 6" cells with a three-busbar design, this can lead to a total silver paste lay-down for bifacial cells of 1g (of which 40% is used for the busbars), or 0.5g for monofacial cells using sputtered silver at the rear. These values are divided by two when using a five-busbar design, and with the use of the most recent paste with higher conductivity the amount is likely to drop to below 200mg per side. However, with such standard soldering, SHJ metallization is clearly a limiting cost factor [26].

Today, the ribbon interconnection can be glued using electrically conductive adhesives or conductive films with a production tool, while maintaining the same reliability as for soldering [27–31]. The glueing techniques have two main advantages. The first is that the screen printing of busbars can be omitted, leading to what is referred to a *busbarless cell design*, in which the ribbons directly contact the screen-printed fingers through an adhesive [24,25]. The total silver consumption for a bifacial cell can therefore be reduced to 0.3g or 0.2g in the four- or five-ribbon case respectively. In the five-ribbon case, the silver cost is reduced to \$0.1/wafer and \$0.018/Wp (assuming a silver price of \$500/kg and a cell efficiency of 22%). The second advantage of a gluing approach is that because no soldering is involved, textured ribbons can be used, which allows the recycling of the light falling on the ribbon, increasing the module power by up to $2\%_{rel}$. [32,33].

Multiwire interconnection

Wire-based interconnection technology is now becoming a very popular alternative to ribbons, as it can decrease the power losses in the metallization grid, reduce interconnection shadowing, improve module reliability against cell cracking, and increase module power output by 3 to $4\%_{rel}$. [15,34].

"SWCT is perfectly suited to SHJ solar cell interconnection, since the soldering is performed during the lamination step."

The SmartWire Connection Technology (SWCT) from Meyer Burger (see Fig. 5) consists of a low-melting-point alloy coated on copper wires which are supported by a polymer foil; the technology was initially developed by Day4 Energy [35]. SWCT is perfectly suited to SHJ solar cell interconnection, since the soldering is performed during the lamination step [16,36]. The distance between wires is only 8mm, which allows the finger line resistivity to be as high as $10\Omega/cm$; in pilot production, the line width can be decreased to under 50µm and the total silver paste lay-down for bifacial cells can be reduced to less than 60mg [36,37]. With only 60mg of silver in total per bifacial cell using SWCT, the metallization and interconnection costs are significantly lowered, and SHJ technology becomes cost competitive compared with standard diffused cells [26]. Recently, Zhao et al. demonstrated a conversion efficiency of more than 23% for a cell batch in pilot production, measured with GridTouch, and recorded 320Wp for a bifacial module with a black background, 330Wp with a white backsheet, and 379Wp with a 20% back-side albedo [19] (see Fig. 5).

Notably in the last few years, extensive work has enabled in particular a significant reduction in the cost of the wire, defining a new generation SWCT, enabling all IEC accelerated ageing tests performed at TÜV Rheinland to be passed multiple times, bringing a multiwire solution highly performing, highly reliable and cost effective [38]. This type of multiwire approach is hence likely to be the best, in terms of readiness and lowest cost, for wide-scale metallization of SHJ, while preserving the advantage of lean cell processing.

SWCT further opens up the possibility of implementing new metallization technologies in the solar industry, as the requirement regarding line resistivity is reduced. In this respect, copper paste screen printing [39], silver nanoparticle inkjet printing [40] and flexographic printing [41] have been implemented in PV modules at the R&D level. SWCT can even contact directly the TCO at the SHJ cell surface; this could allow the metallization step to be completely eliminated from the cell production line. An efficiency of up to 20% for an active module and a reliability over 200 thermal cycles have been demonstrated with such an approach [42].

Copper electroplating

A different approach to further improving the performance of SHJ metallization is to replace the silver paste screen printing by the electrodeposition of copper. Although this technique is already well reported in the literature for homojunction solar cells, its application to SHJ solar cells is more recent and involves a total redevelopment of the processes because of the very different device architecture [43,44]. Indeed, a major difference between SHJ solar cells and their diffused-junction counterparts is the presence of the conductive TCO film at the solar cell surfaces, which cannot act as a plating mask, unlike the dielectric anti-reflection coating layer in the diffused-junction case. Moreover, if direct electrodeposition on the TCO is considered, the adhesion of copper may be problematic and will require either specific pre-treatment [45,46] or a thin electroplated nickel layer [44]. However, even with the addition of a nickel-plated adhesion layer, evidence of micro-voids has been found, which might lead to reduced finger adhesion [44].

Another approach is based on depositing a conductive seed layer by physical vapour deposition (PVD) [47]. In addition to providing an adhesion layer with the underlying TCO, this film exhibits a high lateral conductance (a few Ω/sq., compared with possibly several hundred Ω/sq. for a TCO layer). Therefore, the electrical current for the electroplating can easily be homogeneously distributed over the solar cell surface, and the electrical contact can be directly made on the seed layer. This allows plating on either the n-side or the p-side, without the requirement of using light-induced plating, as well as simplifying the simultaneous plating of both sides in the case of a bifacial solar cell.

As a consequence of the conductive nature of the TCO films, a patterning technique forming an insulating layer everywhere except where the fingers need to be grown is required. Although traditional photolithography has often been used for this purpose in research, achieving ultra-narrow geometries down to 15µm, its potential application in an industrial context remains uncertain because of the high cost of chemicals and its overall complex process flow [44]. With this in mind, several alternatives have been proposed, such as:

- Low-cost photolithography using dry photosensitive film [47].
- Screen printing of an insulating mask [48].
- Dielectric mask and laser transfer [49].
- Inkjet printing of a functional ink (which prevents the cross linking of an underlying resist layer) [45].
- Inkjet printing of hot-melt mask [50].

With the use of the hot-melt film technique, Hermans et al. reported a finger width of less than 20µm. As mentioned in that study, a critical aspect in lowering the processing cost is to ensure a low consumption of hot-melt masking ink; this was accomplished by using a two-step approach, where a thin layer of masking ink is used and only thickened in the finger vicinity in order to properly define the edges, allowing the amount of masking ink to be reduced by more than 70% [50]. An illustration of this process is shown in Fig. 6, where an SHJ precursor is coated on both sides with a metallic seed layer. During the first step of inkjet printing, a thin layer of hot melt is deposited, followed by a second inkjet printing step, in which the finger geometry is accurately defined. The fingers are then grown by electroplating. It is noted that in the bifacial case, both sides of the solar cell can be processed simultaneously. Finally, the hot-melt plating mask and the excess seed layer are chemically removed.

Source: CSEM

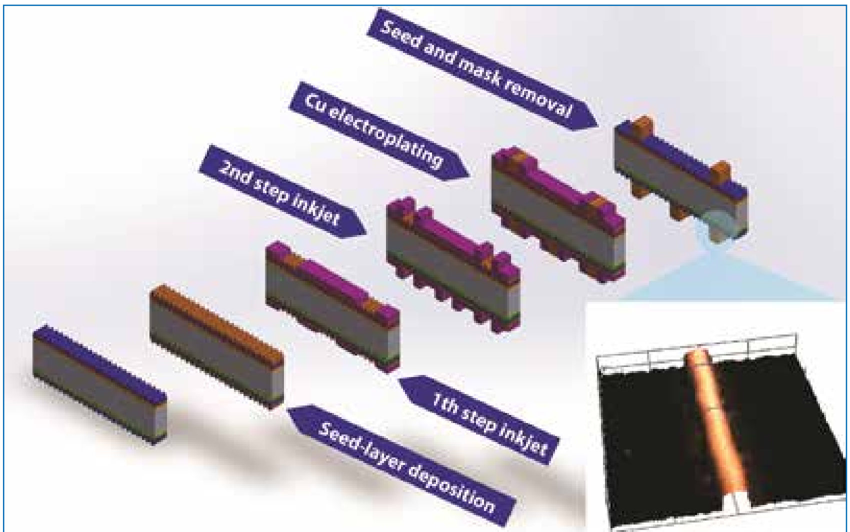


Figure 6. Process flow for the copper electroplating of a bifacial SHJ solar cell.

Credit: Meyer Burger

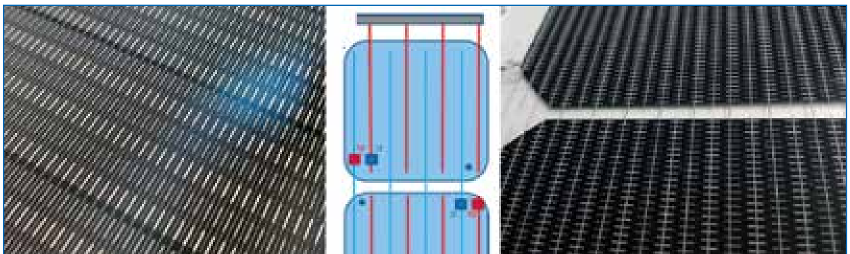


Figure 7. Multiwire interconnection of back-contacted silicon heterojunction solar cells developed with the support of the Swiss-CTI. Courtesy of Meyer Burger.

> "Remarkable efficiencies have recently been achieved by using copper electroplating for the metallization of SHJ devices."

The copper electroplating metallization technique offers several benefits. First, the paste spreading issue encountered during screen printing is completely absent; this means that, in combination with the use of an appropriate patterning technique, the finger width, as well as the shadowing induced by the metallization grid, can be significantly reduced. Second, as the resistivity of electrodeposited copper is close to the electrical resistivity of pure copper, highly conductive lines can be produced. As a result, remarkable efficiencies have recently been achieved by using copper electroplating for the metallization of SHJ devices – for instance, 25.1% by Kaneka, and 23.1% for Silevo, a company acquired by SolarCity (now Tesla) in 2014 [5,51]. At the module level too, copper plating gives rise to impressive efficiencies, as demonstrated by Sunpreme with a record efficiency of 402Wp for a bifacial module incorporating 72 SHJ cells [52].

As shown in Fig. 2, a line resistivity below 0.5Ω/cm can be achieved using this technique, which allows the design of a metallization grid with a finger length longer than that for other metallization techniques and enables the use of an interconnection with two or three busbars. Even more importantly, in the case of a shingled-cell interconnection, copper electroplating allows the cell to be cut into a minimum number of subcells, thus reducing the losses induced by the cutting process.

SHJ interdigitated back-contact

IBC-SHJ architecture has recently attracted a lot of interest with, in particular, the achievement of energy conversion efficiencies of 26.7% and 25.6% at the cell level by Kaneka and Panasonic respectively [4,6,7]. Kaneka has also reported a world-record module conversion efficiency of 24.37% [53]. Regarding the metallization of such devices, different strategies exist. One option is to use two interdigitated metallization combs with busbars on each side. Although the metallization lines can be larger than in the metallization grid discussed earlier, their length of ~15cm in the case of 6" solar cells entails the use of a substantial amount of metal in order to prevent significant electrical losses in the fingers. This can be realized by electroplated highly conductive lines. Copper layers with ultralow tensile stress are necessary, enabling finger heights of a few tens of microns on 6’’wafers, without introducing wafer bending as obtained e.g. from electrolytes developed at CSEM [54].

The most elegant solution to avoid important metallization at the back side of the IBC cell is, however, to use two levels of multiwire interconnection instead. For this, only two or three screen-printing steps are necessary for producing silver fine line, conductive pads and isolation pads (see Fig. 7). Each odd and even wire will contact the p and n polarities respectively, and the order is reversed on the neighbouring cells. A second notable advantage of this interconnection approach is the possibility of having bifacial back-contacted solar cells. Within the Next-Base project, the European Union firmly supports the development and implementation of such advanced metallization and interconnection concepts for IBC-SHJ solar cells [55].

Conclusions

Different materials and techniques brought to industrial maturity can be used for the metallization of SHJ solar cells. In particular, low-temperature-cured silver pastes have undergone extensive development in recent years, with lower minimum bulk resistivities of just three times the resistivity of pure silver having been achieved. Importantly, the interconnection scheme used during module manufacturing alters in a significant way the requirements regarding line resistivity. In this respect, the multiwire approach decreases the limitations related to finger resistivity, allowing the use of fine-line screen printing; this technique enables considerable reductions to be made in silver paste consumption and optical shadowing, ultimately yielding higher module performance. For the implementation of a wider variety of interconnection technologies and approaches, an alternative metallization technique, such as copper plating, should be considered. Copper plating is well suited, for instance, to the use of existing interconnection equipment with a small number of busbars or for shingled modules: narrow, but still highly conductive, fingers are achievable, thus minimizing the shadowing due to the metallization.

"The production costs associated with SHJ technology are shrinking, making it one of the most cost-competitive PV technologies for energy production."

To conclude, SHJ technology has already demonstrated a reduced levelized cost of electricity (LCOE) thanks to the native bifacial architecture and the low thermal coefficient. Now, with the recent findings and developments in the field of metallization and interconnection, the production costs associated with SHJ technology are shrinking, making it one of the most cost-competitive PV technologies for energy production.

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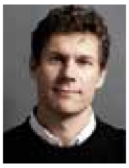

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