Multi-busbar technology: Increased module power and higher reliability at lower cost

Sebastian Schindler, Fraunhofer CSP, Halle, & **Michael Volk**, SCHMID Group, Freudenstadt, Germany

ABSTRACT

Recent advances at the cell level and in tabber-stringer equipment have led to the development of the next generation of cell interconnection architecture, resulting in an increase in cell and module performance. The multi-busbar (MBB) concept discussed in this paper delivers the benefits of a saving in material costs, a reduction in total series resistance and an improved light utilization for higher performance at lower cost. The combination of the cell and module concept and the stringer equipment works for a wide variety of cell types and enables an appreciable decrease in cost per watt and module size per watt.

Introduction

There are several clear indications of the effect of changes to the cell interconnection process and overall module architecture. New cell metallization layouts and techniques enable higher efficiencies to be achieved at the cell level, while the latest research in module interconnection schemes – such as half-cut cells – has led to improvements in module power output by decreasing cell-to-module losses [1,2]. Equipment suppliers are offering new process lines to upgrade the state-of-the-art three-busbar cell design with at least four, or even five, busbars.

This paper describes multi-busbar (MBB) technology developed by SCHMID Group as a more refined serial solar interconnection concept. Cell-to-cell interconnection is realized by 15 Cu wires, following the alternating front-side to back-side connection through a stringing and soldering process. The equipment and interconnection process is discussed, complemented by microstructure diagnostics to verify contact formation and reliability.

The proposed technique aims to reduce the amount of silver (Ag) needed for the front cell electrode. With the multi-busbar design, module performance can be increased because of the reduction in the total series resistance of the interconnected cell strings and also because of improved light utilization owing to the round wires.

There are four key advantages to using MBB technology for photovoltaic cells and modules:

1. A reduction in the amount of Ag per cell required for different cell types.
2. Higher cell and module efficiencies because of the new cell metallization layout and multi-busbar stringing design.
3. Adaptable equipment for retrofitting existing module production lines, a reliable stringing process, and conventional string lay-up and module lamination.
4. Improved module reliability and reduced thermomechanically induced stresses and cell breakage.

> "With the multi-busbar design, module performance can be increased because of the reduction in the total series resistance of the interconnected cell strings."

This paper gives a summary of the benefits from a cell perspective, and an overview of the equipment for implementing the multi-busbar interconnection process, as well as the overall module production process. Furthermore, results of micro-mechanical and micro-structural diagnostics of the miniaturized solder joints are presented. The last section focuses on forthcoming work, which will address the mechanical and reliability advantages of multi-busbar interconnection technology.

Cell development and metallization concept

In 2010 Ag usage for photovoltaic applications reached approximately 7% of the annual worldwide supply of this material [3]. At the same time as the usage of Ag has been rising, the price of Ag has been increasing: this poses an important limitation on the growth of solar cell production at lower costs. Thus, a key goal for the photovoltaic industry is to decrease the amount of Ag usage in solar cell production [4].

The multi-busbar design demonstrates a potential for cell and module efficiencies higher than those achievable with the state-of-the-art three-busbar cell design [5]. The multi-busbar design is optimized so that the shaded area and Ag consumption are reduced. The proposed layouts are based on small solder pads and a grid finger scheme, instead of continuous busbars as a soldering pad for the Cu ribbons. New test and measurements set-ups have also been developed [6].

In conventional three-busbar layouts, the length of the fingers between the busbars along with the associated ohmic losses limit the minimum finger width and therefore determine the amount of Ag required to achieve sufficient fill factors. With the reduced finger lengths of the multi-busbar design it is possible to tap the full potential of modern metallization techniques, such as fine-line screen printing or inkjet seed-layer printing combined with light-induced plating. The obvious benefits are a high fill factor with significantly reduced Ag consumption and less shading of the active area [7].

Two different processes are used for the metallization of the solar cell: 1) fine-line screen printing, and 2) seed-layer and plating techniques of the front electrodes [8]. Table 1 compares the amount of Ag required for the multi-busbar layout with that for a three-busbar layout. With improved alignment and fine-line and dual printing, the screen-printing process has gradually been improved and the printing paste consumption reduced

	Group 1 (MBB layout)	Group 2 (MBB layout)	Group 3 / Reference (three-busbar layout)
Screen printing	30–33mg finger paste		
	30–32mg pad paste		
Seed layer		8–9mg	11–12mg
Base layer		20–25mg	85–90mg
Total	60–65mg	28–34mg	96–102mg

Table 1. Total amount of Ag consumption for the different types of front-side metallization, according to Braun et al. [8].

over the years: a reduction of 40% has been realized. For the other approach of seed-layer inkjet printing and Ag plating, only one third the amount of Ag is needed. The results have confirmed the formation of a sufficient front electrode on the solar cells, leading to an even greater reduction in Ag.

The overall metallization design on the front side is very flexible. The metallization pattern is highly adaptable to specific customer layouts, process requirements (pad size vs. alignment, etc.) and optimized cell efficiencies. Figs. 1 and 2 show two different metallization layouts: seed-layer inkjet printing and plating, for which a standard busbar-less small meshed layout was chosen; and screen-printed contacts, for which an improved design, with a further reduction in the number of pads, has been developed.

The results showed that the amount of Ag can be drastically reduced; moreover, the multi-busbar concept measures up to the proposed long-term goals in international roadmaps: the 'International technology roadmap for photovoltaic' (ITRVP) [4] indicates a target of 50mg of Ag per cell in 2020.

Cell stringing process and multi-busbar connector

A multiple busbar concept with small Cu wires for cell interconnection was first proposed by the Canadian company Day4Energy [9]; this technology is now promoted by Meyer Burger under the name of 'smart wire connection' [10]. The smart wire approach combines the stringing and lamination process into one step, bonding indium-coated wires to the solar cells.

In comparison, the multi-busbar connector discussed in this paper is similar to a classical stringer step followed by a standard lamination process: the solar cells are still interconnected in an alternating way, from the front side of one cell to the back side of the adjoining cell. The cells are mechanically and electrically interconnected by 15 Cu wires, and assembled into conventional cells strings; they are then picked and placed for further module assembly (cross interconnection and encapsulant lamination). This has the advantage that the overall advances in technology can be implemented in existing production lines: the equipment can integrated, with only the need to replace tabber-stringer equipment.

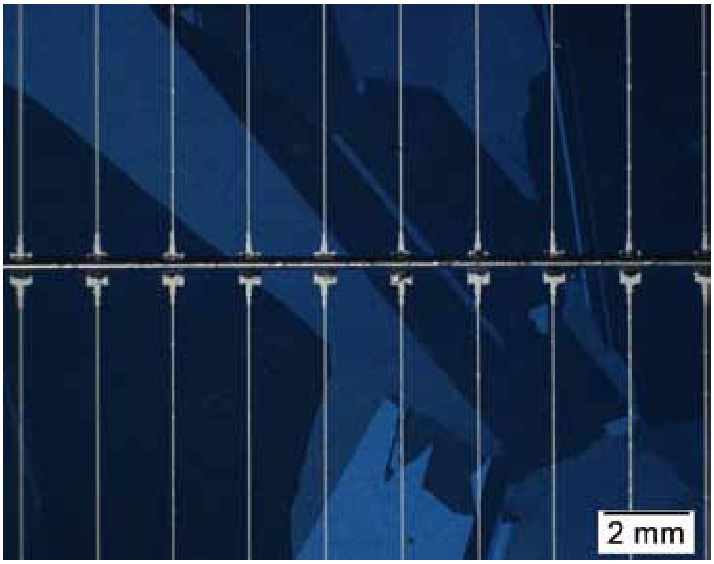

Figure 1. Ag-plated contacts: standard busbar-less design, with soldering pads on the grid fingers.

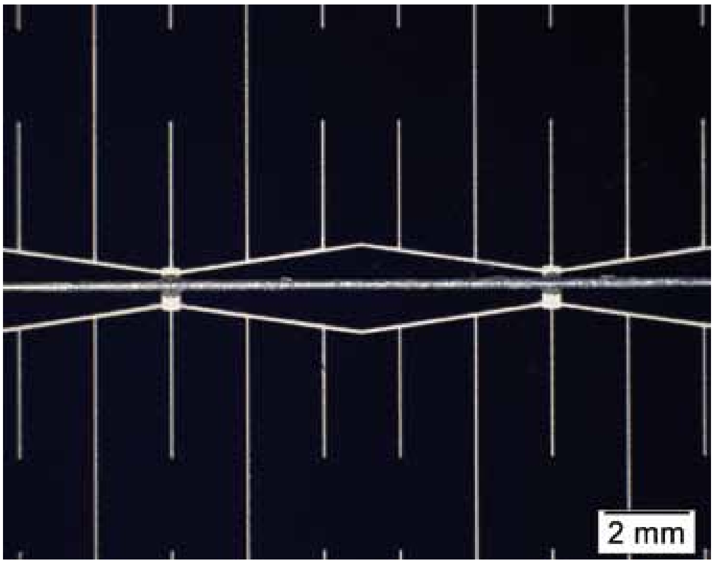

Figure 2. Ag screen-printed contacts: improved design, with a reduced number of solder pads and a more complex grid finger layout.

> "Advances in technology can be implemented in existing production lines."

With the multi-busbar development at the cell level, a new generation of process equipment [11] for the cell-to-cell interconnection was necessary in order to meet the requirements for connecting small Cu wires on busbarless cells. Since the alignment of the cells and the wires is crucial, the multi-busbar stringer uses high-precision image processing to determine the position of the metallization pattern. The string assembly is carried out on preheated vacuum chucks via IR soldering (see Fig. 3). All 15 tin-coated Cu wires are soldered to the front and back sides of the cell in one step, as shown in Fig. 4. To enable easy assembly of the module matrix, the 15 wires at both ends of the strings are automatically interconnected by an end ribbon. Fig. 5 shows an SEM image of Cu wires with the pointwise solder joints on the multi-busbar cell metallization pattern.

PV module assembly process

As already mentioned, the overall module assembly process follows a state-of-the-art workflow. The metallization process, the cell inspection and measurement, and the tabber-stringer process equipment are subject to change, but the subsequent string cross-connection to the junction box and the module lamination are standard.

Fig. 6 shows the process flow of the multi-busbar module manufacturing concept, with the changed processes marked on the flow chart. No additional steps are necessary to realize the multi-busbar cell/module concept, compared with current conventional PV cell and module assembly processes. At the cell fabrication level, only the metallization process is modified: a screen-printing process is still used, but new screen masks are necessary. For quality control and inspection, a new contacting unit is required because of the modified front-side layout of the multi-busbar cell.

For module production, only new stringing equipment has to be installed, so production can be easily ramped up. In the lay-up process the cell strings are placed onto the glass. A minor adaptation of the cell string interconnection needs to be performed to cross-link the 15 multi-busbar Cu wires.

Contact formation and evaluation of solder joints

Besides the benefits at the cell level, extensive studies relating to contact formation, process and material interactions, and reliability assessment have been carried out to optimize

Figure 3. Multi-busbar connector: vacuum chuck used to align the 15 Cu wires on the solar cell.

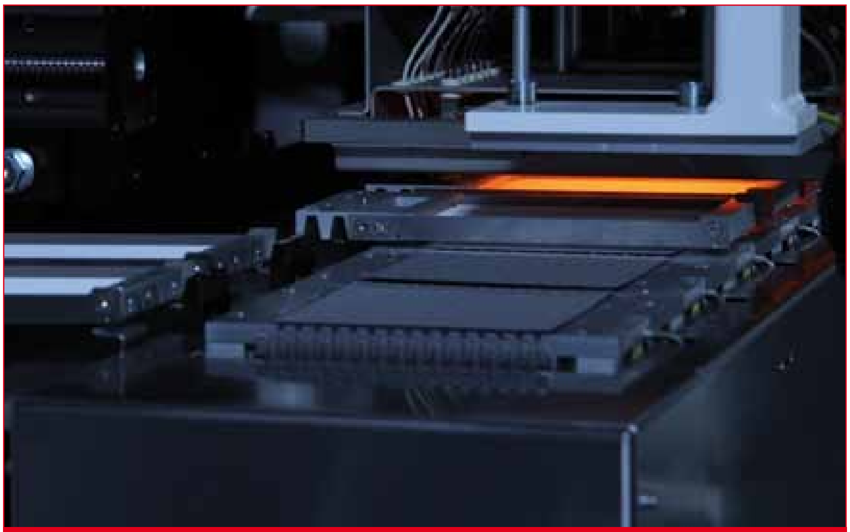

Figure 4. Multi-busbar connector: cell vacuum chucks and the IR soldering unit for the soldering process.

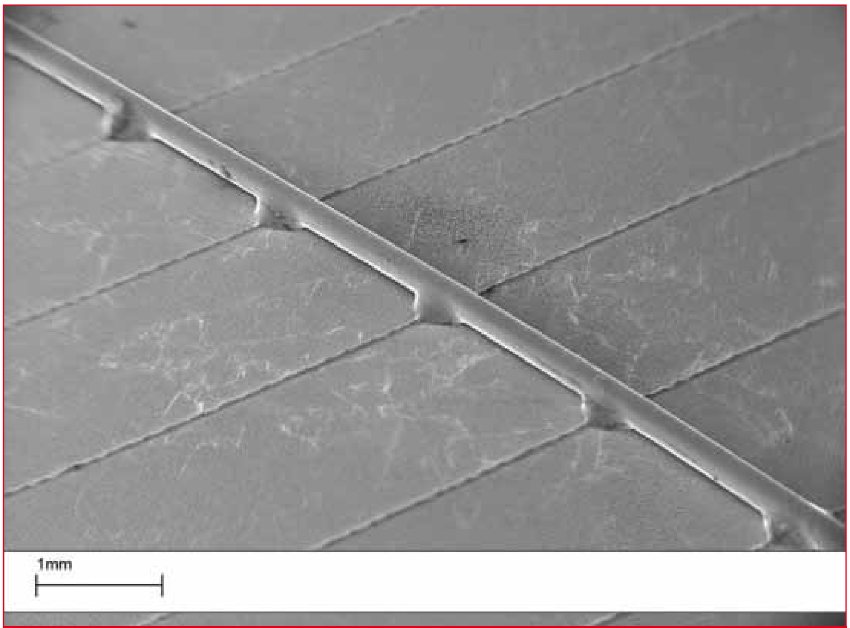

Figure 5. SEM image of Cu wires soldered to the multi-busbar cell metallization pattern.

and validate the module concept. In a recent work by Schindler et al. [12], the contact formation of the soldering process was investigated for the MBB cell metallization design. Different technological approaches, such as varying the Cu wire diameter or the cell metallization, were evaluated by means of micro-mechanical pull tests.

By drawing upon expertise in microelectronics and microsystems technology for failure diagnostics, as well as a material evaluation of adhesion technologies and system integration (e.g. wire bond contacts or welded contacts), a universal tool (see Fig. 7) was co-developed [13] to characterize the solder contact strength of solar cell interconnections (both standard H-pattern cell layouts and new cell metallization concepts and layouts). This mechanical testing of the MBB solder joints was evaluated by a pull test of the miniaturized solder joints, as this is a suitable way of testing the influence of process parameters and material mixtures for interconnections. Force measurements of the pads were conducted on the solar cell front-side metallizations (see Fig. 8). The single-point pull-force interconnection values for the sequences were assigned maximum values, and the mean value and standard deviation for the measured specimen were calculated. In addition, the fracture mode after the pull test was recorded in order to seek a possible correlation between the force values and the mechanically induced contact deterioration within the test regime.

The measurements indicated good force values for these miniaturized contacts. The results also showed that the metallization process plays an important role in mechanical strength during pull tests of the solder joints.

> “The results showed that the metallization process plays an important role in mechanical strength during pull tests of the solder joints.”

The solder joints on inkjet seed-layer printed and Ag-plated pad structures resulted in lower pull force values than when screen-printed Ag metallization was used. For the screen-printed contact pads, the pull forces are above 1N, with values over 2.5N being measured for several contacts (Fig. 9). The solder joints using the inkjet seed-layer printing and Ag-plating technology resulted in a pull force mean value of around 1N in the mechanical tests.

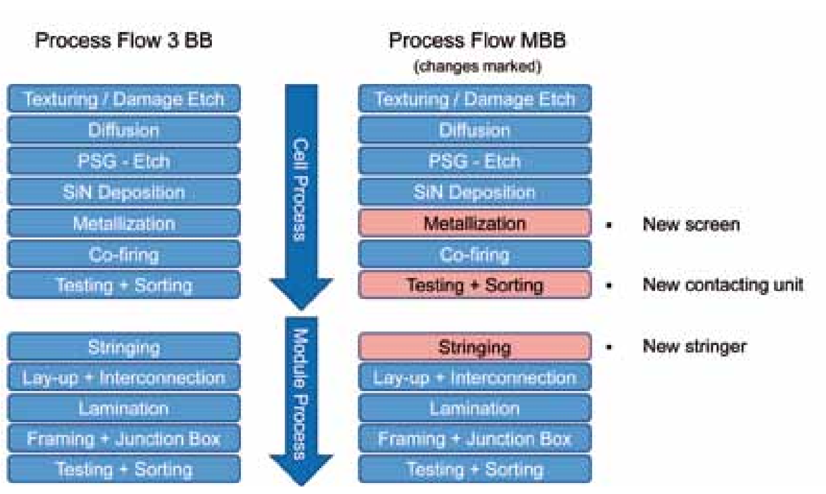

Figure 6. Process flow of multi-busbar cell manufacturing and module assembly steps.

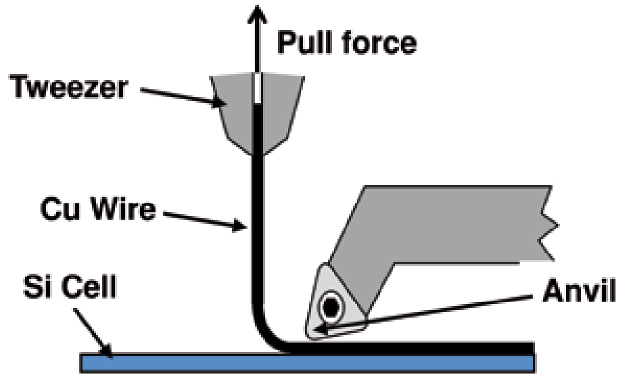

Figure 7. Test set-up for the mechanical pull tests.

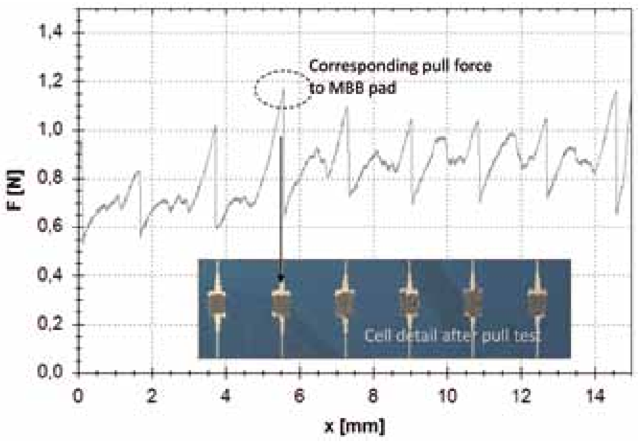

Figure 8. Typical force-pad sequence of the contact force measurements, showing that the wire had been soldered to every single pad.

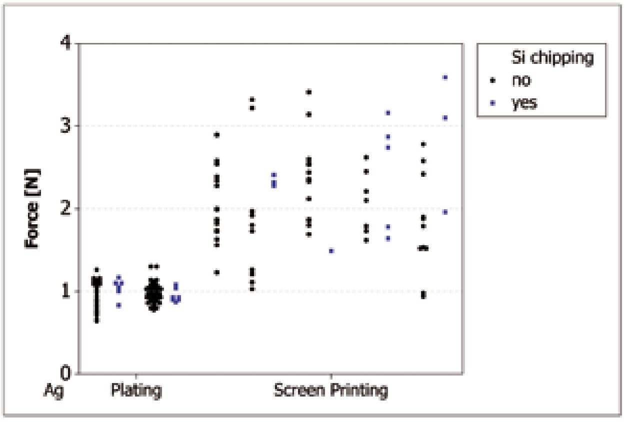

Figure 9. Force values of the single solder pads for the two metallization types, with documented Si chipping.

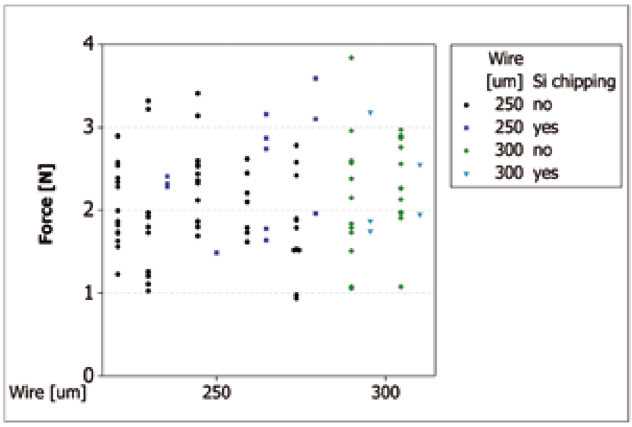

Figure 10. Force values of the single solder pads for two wire diameters, with documented Si chipping.

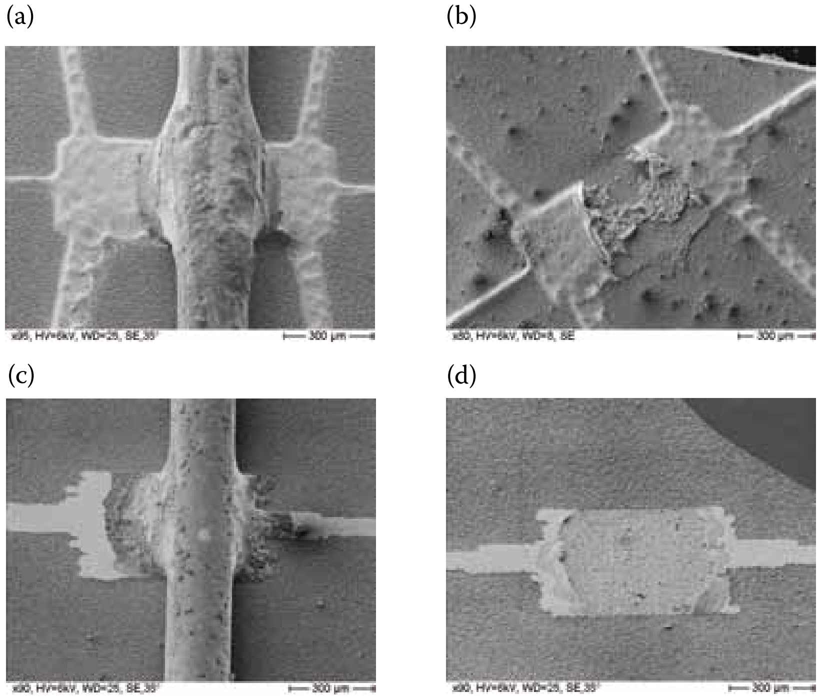

Figure 11. SEM images of soldered Cu wires in cell metallization pads, and their main fracture mode after the pull test: (a-b) screen printing; (c-d) Ag plating.

To compare the peel force values of multi-busbar solder joints and standard ribbons, the width of the soldered area has to be taken into account. The contact area width of about 600µm is 40% of the width of a typical three-busbar ribbon (1.5mm).

No significant difference in quality of the soldered contacts could be observed when the Cu wire diameter was varied (Fig. 10): similar results for wires of two different diameters were obtained when soldered with the production equipment.

A detailed analysis of the contact fracture modes after the pull test revealed considerable differences in the two types of metallization (Fig. 11). Wire diameter variation did not have a significant influence on the fracture mode after the pull test.

The screen-printed solder pads exhibited significant residues of the metallization and side-wall solder residues of the solder meniscus. The inkjet seed-layer printing and Ag-plated pad structure was completely separated from the cell after the test, and the cell surface structure was visible. Partial Si chipping within the soldered area on the specimen was noted. This conchoidal fracture mode was observed for both metallization types (see Fig. 12), but could not be correlated with specific force values.

The contact formation of the solder joints was analyzed by means of microstructural diagnostics. The SEM images (Fig. 13) verified that the soldering results of the tabber-stringer equipment were homogeneous. The tin coating of the Cu wires always wetted on the metallization pad area, and a uniform meniscus from the Cu wire to the solder pad was visible.

The metallographic cross sections in Fig. 14 show in detail the solder meniscus of the solder joints. The solder meniscus solidified to a uniform shape from the Cu wire to the pad area, and no dewetting or dissolution of the Ag metallization could be detected. The solder joint volumes are significantly larger than for conventional interconnected solder joints with tin-coated Cu ribbons; from the stress relaxation and material science point of view, this feature is assumed to be of additional benefit to contact reliability, and therefore to overall module performance and reliability.

Conclusions and further work

The new metallization layout has proven benefits of higher cell efficiencies, invariably associated with a reduction in the amount of Ag needed for the front cell electrode.

Two technical approaches – fine-line screen printing, and seed-layer inkjet and light-induced plating – enable new cell metallization layouts with significantly reduced finger widths and cross sections.

> “The new metallization layout has proven benefits of higher cell efficiencies.”

The pointwise stringing process produced reliable soldered contacts for both cell metallization and wire types. Further investigations will be carried out to verify the overall machine set-up with regard to robust and repeatable soldering parameters.

Micro-mechanical testing of the solder joints was carried out by means of a pull test, which is a suitable method for testing the mechanical solder joint strength of the contacts. The pull test measurements, especially for screen-printed MBB structures, yielded good pull forces for the miniaturized solder contacts [14,15]: the values were comparable to (or better than) the results for three busbars on a per width basis. The metallization process plays an important role in the mechanical strength of the solder joints during pull tests. The solder joints with Ag-plated pad structures exhibited lower pull forces than with screen-printed Ag metallization. For the screen-printed contact pads, the pull forces were greater than 1N, and values over 2.5N were even obtained for several contacts. Solder joints with the inkjet seed-layer printing and light-induced Ag-plating technology yielded a mean value of around 1N in the mechanical tests. All contact configurations demonstrated very good wetting of the solder from the Cu wire to the pad area. The multi-busbar connector equipment produced a uniform solder meniscus on the pad areas. The measured pull forces do not depend on the diameter of the Cu wires (250µm vs. 300µm), but optimization of the wire diameter, for either reduced shading or lower series resistance, is possible.

The determination of the minimum pull force which is still compatible with module reliability will be the subject of further investigations. Clearly, different metallization technologies might show

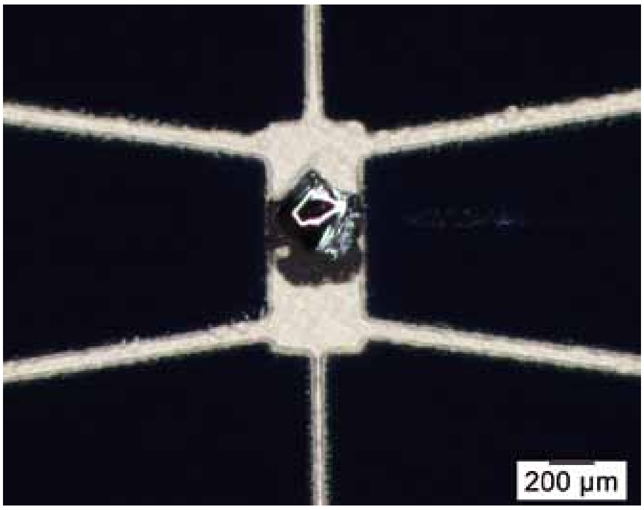

Figure 12. Detailed microscopy image of the fracture mode after the pull test, with conchoidal fracturing of silicon within the pad area.

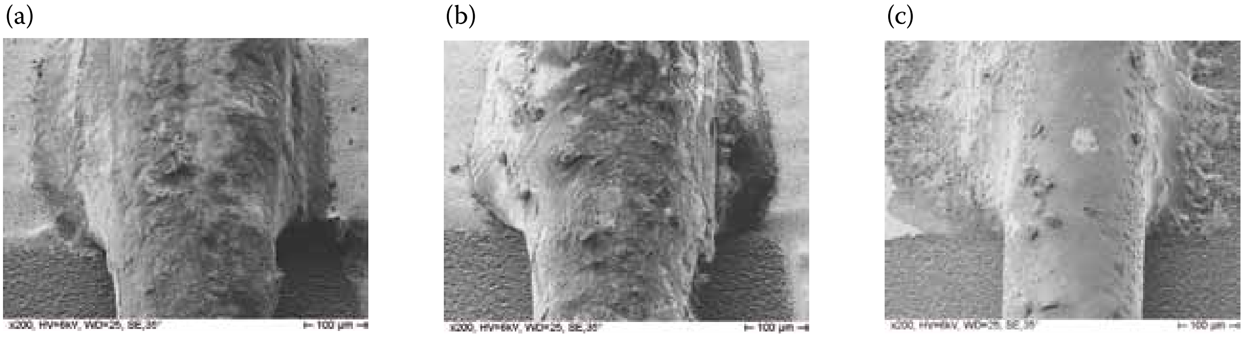

Figure 13. SEM images of soldered Cu wire in cell metallization pads: (a) screen printing, 250µm Cu wire; (b) screen printing, 300µm Cu wire; (c) Ag plating, 250µm Cu wire.

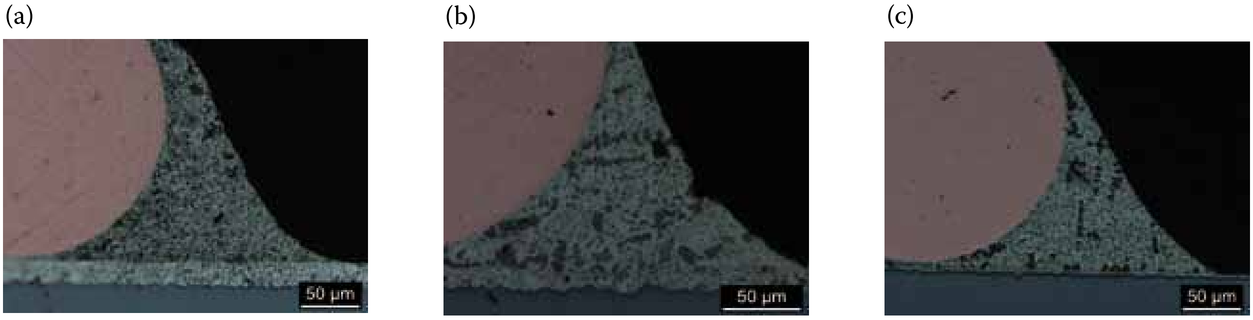

Figure 14. Cross sections of soldered Cu wire in cell metallization pads, and their main fracture mode after the pull test: (a) screen printing, 250µm Cu wire; (b) screen printing, 300µm Cu wire; (c) Ag plating, 250µm Cu wire.

different minimum pull forces.

Further investigations of the influence of cell breakage and induced stresses on the soldering are in progress. A combination of in situ electroluminescence (EL) measurements and four-point bending apparatus is therefore proposed for evaluating the contributing factors of cell breakage due to process parameters, module layout and combinations of materials used [16].

It is assumed that multi-busbar metallization structures will reduce mechanically induced stresses within the cell: the probability of cell breakage will therefore be reduced. The mechanical stress on the solder joint will increase, but, because of the benefits of significantly larger solder volumes, the potential for relaxation and stress restraint is increased. Further investigations are ongoing and will be the subject of forthcoming publications to prove the benefits and reliability of the multi-busbar module technology.

References

[1] Oswald, M. et al. 2013, "Evaluation of silicon solar cell separation techniques for advanced module concepts", *Proc. 28th EU PVSEC*, Paris, France.

[2] Guo, S. et al. 2013, "A quantitative analysis of photovoltaic modules using halved cells", *Int. J. Photoenergy*, Vol. 2013.

[3] Green, M.A. 2011, "Ag requirements for silicon wafer-based solar cells", *Prog. Photovolt.: Res. Appl.*, Vol. 19, pp. 911–916.

[4] SEMI PV Group Europe 2013, "International technology roadmap for photovoltaic (ITRVP): Results 2012", 4th edn (March) [available online at http://www.itrpv.net/Reports/Downloads/].

[5] Braun, S. et al. 2013, "Multi-busbar solar cells and modules: High efficiencies and low silver consumption", *Energy Procedia*, Vol. 38, pp. 334–339.

[6] Herguth, A. et al. 2013, "Towards non-permanent contacting schemes for busbar-free solar cells", *Proc. 28th EU PVSEC*, Paris, France.

[7] Braun, S., Micard, G. & Hahn, G. 2012, "Solar cell improvement by using a multi busbar design as front electrode", *Energy Procedia*, Vol. 27, pp. 227–233.

[8] Braun, S. et al. 2013, "Highly efficient multi-busbar solar cells with Ag nano-particle front side metallization", *Proc. 28th EU PVSEC*, Paris, France.

[9] Schneider, A., Rubin, L. & Rubin, G. 2006, "Solar cell improvement by new metallization techniques – The DAY4TM electrode concept", *Proc. 4th WCPEC*, Waikoloa, Hawaii, USA, pp. 1095–1098.

[10] Söderström, T., Papet, P. & Ufheil, J. 2013, "Smart wire connection technology", *Proc. 28th EU PVSEC*, Paris, France.

[11] SCHMID Group 2012, "SCHMID presents multi busbar connector prototype at PVSEC", Press Release, September 18th.

[12] Schindler, S. et al. 2013, "Soldering process and material characterization of miniaturized contact structures of a newly developed multi busbar cell metallization concept", *Proc. 28th EU PVSEC*, Paris, France.

[13] Klengel, R. et al. 2011, "Evaluation of the mechanical strength of solar cell solder joint interconnects and their microstructural properties by developing a new test and inspection equipment", *Proc. 26th EU PVSEC*, Hamburg, Germany.

[14] DIN EN 50461 (2006), "Solar cells – Datasheet information and product data for crystalline silicon solar cells".

[15] DIN EN 61189-2 (2006), "Test methods for electrical materials, printed boards and other interconnection structures and assemblies – Part 2: Test methods for materials for interconnection structures" (IEC 61189-2:2006).

[16] Sander, M. et al. 2013, "Systematic investigation of cracks in encapsulated solar cells after mechanical loading", *Solar Energy Mater. & Solar Cells*, Vol. 111, pp. 82–89.

About the Authors

Sebastian Schindler joined Fraunhofer CSP in 2008 and is currently a researcher in the module technology group. He studied electrical engineering at the Technical University Dresden, specializing in electronics packaging. For the past few years Sebastian has worked in the field of process development and material characterization for solar interconnection; he is now also involved in back-contact cell projects, as well as working on alternative module technology and assembly processes.

Michael Volk studied physics in Hamburg and Hanover, and received his Ph.D. in 2005. He began his career in the PV industry in 2007, joining the R&D team at Solar Systems Pty Ltd in Melbourne, Australia, where he worked on the development of concentrator PV systems. Before taking on the role of product manager for the multi-busbar connector at SCHMID Group in 2013, Michael was head of the product engineering department at SCHOTT Solar in Alzenau, Germany.

Enquiries

Fraunhofer CSP
Otto-Eißfeldt-Str. 12
06120 Halle
Germany

Tel: +49 345 5589 5523
Email:
sebastian.schindler@csp.fraunhofer.de
Website: www.csp.fraunhofer.de