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Cite as: AIP Conference Proceedings **2367**, 020001 (2021); https://doi.org/10.1063/5.0055981
Published Online: 01 June 2021

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Summary of the 9th Workshop on Metallization and Interconnection for Crystalline Silicon Solar Cells

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Abstract. The 9th edition of the Workshop on Metallization and Interconnection for Crystalline Silicon Solar Cells was held as an online event but nevertheless reached the workshop goals of knowledge sharing and networking. The technology of screen-printed contacts of high temperature pastes continues its fast progress enabled by better understanding of the phenomena taking place during printing and firing, and progress in materials. Great improvements were also achieved in low temperature paste printing and plated metallization. In the field of interconnection, progress was reported on multiwire approaches, electrically conductive adhesives and on foil-based approaches. Common to many contributions at the workshop was the use of advanced laser processes to improve performance or throughput.

INTRODUCTION

By all accounts, 2020 was an exceptional year. The global pandemic impacted the lives of millions and drastically changed our way of living and modes of operation. But in 2020 we also witnessed unprecedented heat, fires and floods, all pointing at an accelerating effect of climate change. There were however glimmers of hope. In spite of the crisis, solar energy, one of the key technologies to reduce greenhouse gas emissions, maintained a high deployment rate in 2020. The International Energy Agency recognized the fantastic progress in photovoltaics, referring to it as the 'king of electricity' and projecting a fast-increasing share of PV in global generation[1]. Prices of solar electricity from solar parks in countries with high insolation have decreased to historically low values, lower than for any electricity generation ever. But in other countries as well, PV electricity competitiveness is improving year after year. This is powered by scale effects in mass manufacturing, but also by astounding technological progress and fast industrial implementation. Monocrystalline silicon Passivated Emitter and Rear Cells (PERC) solar cell technology has become the workhorse of the industry in the last two years and is presently dominating new solar cell capacity installations. As recently pointed out in an extensive review of PERC technology[2], the high efficiencies of PERC solar cells have been enabled by improvements in metallization and interconnection. The paper also explains the large further performance improvement that is possible, which also relies on progress in how solar cells are metallized and interconnected.

Since 2008, the Metallization and Interconnection Workshop (MIW) has been a key forum where knowledge in the critical fields of solar cell metallization and interconnection is shared. It has taken place every one and a half year since the first workshop and has become a highly recognized event by experts in those fields, appreciated for the quality of the contributions and the discussions and the exceptional networking opportunity. The situation with the Covid-19 pandemic made an in-person 2020 workshop impossible and forced us to reconsider the event format. We

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AIP Conf. Proc. 2367, 020001-1–020001-12; https://doi.org/10.1063/5.0055981
Published by AIP Publishing. 978-0-7354-4101-9/$30.00

used an innovative online platform that enabled not only presentations followed by Q&A but also more informal interactions, where participants could see and talk directly to other participants. The event took place on October 5th and 6th 2020. 117 experts from 22 countries took part and attended 21 contributions presented live. In spite of a few technical glitches, the workshop was successful and the goals of exchanging on the state-of-the-art in research and connecting researchers in the field were achieved.

In this paper we discuss the different contributions in the context of PV trends while giving a general description of the present status in the field. We also present the results of the online survey that was conducted during the workshop. All presentations are available to download at http://www.miworkshop.info/ and some selected contributions are published as journal papers in these AIP proceedings.

PRINTED METALLIZATION

The main technology to achieve contacts on solar cells is screen printing. The technology has enormously improved in the last few years in terms of linewidth, aspect ratio and process speed through development of new screen-printing pastes, screens and equipment. This technological progress, which is continuing at unabated speed, is enabled by detailed scientific study and growing understanding of the key phenomena during contact formation.

Screen Printing of High Temperature Pastes

The majority of solar cells are metallized using ‘high temperature’ pastes, mostly Ag paste for the solar cell front and Al paste for the rear. Every year paste manufacturers release new pastes that enable finer linewidth and lower surface doping concentration. The effect of each paste component is studied in detail, not only in the nominal power operation, but in also in other situations. A presentation at the workshop for instance studied the impact of Al in Ag pastes on the low light performance of solar cells [3, 4]. Another presentation introduced the incorporation of carbon nanotubes into paste formulation in order to keep contact continuity upon cell breakage and in doing so slowing down PV module degradation in operation [5].

There was a strong focus in this edition of the workshop on the screen printing process itself. An important component of this is screen design. Cell makers have many different parameters they can vary to improve screen design to achieve better results in terms of line width, aspect ratio and constant height, such as wire diameter and type, mesh count, screen angle, emulsion thickness, etc. Optimizing the screen design is complex as all parameters have impacts that are interlinked. The optimum designs changes depending on the availability of new materials (e.g. narrower but nevertheless strong and elastic wires for meshes). At the workshop, an ‘evolutionary’ approach to screen design was presented [6], in which designs with a certain combination of parameters are compared with each other. At every iteration in the algorithm, the screen design resulting in the best prints as determined by a model ‘survives’ and is then compared to other designs that have proved ‘fitter for survival’ than others. The algorithm finally points at an optimized design. This method not only confirms the best practice in today’s screen designs used in the industry, but also predicts the design of future screens (when new materials will become available) and the achievable features of prints. The study concluded that there are still many years ahead for steady progress in screen printing.

However, in order to reach linewidths well below 20 µm, the mechanical behavior of pastes during the printing process will need to be fully understood. With a high speed camera study [7], it was shown that the paste, upon being pushed in the openings in the screen emulsion by the squeegee, spreads on the cell surface well beyond the opening in the screen before retracting during the snap-off, and that the final linewidth depends on wetting and rheological properties of the pastes.

The step following printing, namely contact firing at high temperature is also crucial for solar cell performance. Although this process step consisting of transporting cells on a belt through a continuous furnace is well established, it has proved possible to further improve it, boosting throughput by increasing belt speed while maintaining the desired temperature profile, and introducing in-furnace monitoring using inline infrared thermography [8, 9]. An exciting new option to obtain optimal contacts was also presented consisting in using laser illumination, either during, after, or instead of the firing process [8-11]. Through laser illumination, charge carriers are very locally forced through metal-semiconductor contacts, resulting in low contact resistance while keeping surface passivation intact. The full potential of this laser-enhanced contacting process will probably be achieved by combining laser treatment with screen printing pastes specifically optimized for that kind of process. Promising results of such a combined approach were shown at the workshop [10, 11].

Special attention was given to implementing screen printed contact in tunnel oxide passivating contact structures (TOPCon), where the active semiconductor in the device is shielded from the contact metal by engineered thin layer stacks, typically a tunnel SiO_2 layer with highly doped polysilicon on top. Detailed studies analyzed the impact of layer stack and firing parameters on recombination under contacts and contact resistivity, and conditions have been identified in which both low recombination and low contact resistivity can be achieved at the same time [12, 13].

Low Temperature Paste Screen Printing

Next to n-type TOPCon solar cells the technology that is seen as the potential next mainstream after p-type PERC cells is n-type silicon heterojunction (SHJ) cells. Improvements to processes for low temperature pastes are however needed, as SHJ cells are limited in process temperature. Apart from their higher cost, the application of those pastes has been hindered by a slow screen-printing process limiting achievable throughputs and hence costs. It was shown at the workshop that the overall screen-printing process speed could be drastically increased while performance was maintained or even improved, by tuning process parameters and introducing various light soaking approaches [14, 15].

Alternative Printing Techniques

Instead of pushing the limits of screen printing, one can also consider printing these low temperature Ag pastes with an alternative printing technology. One such alternative, parallel dispensing has been developed over the years at Fraunhofer ISE. At this workshop, it was reported that, although it was originally developed for high temperature pastes, the technique could successfully be transferred to low temperature Ag pastes, reaching line widths around 30 µm and SHJ solar cell efficiencies above 22.5% [16, 17]. Importantly, the technology is being transferred to equipment enabling mass production, by integrating parallel dispensing heads in existing screen printers.

The progress on two other alternative printing technologies was also presented, which aim to drastically increase throughput of solar cell printing by switching from flat and sequential printing to rotary and continuous printing. Rotary printing is similar to screen-printing, but the squeegee is stationary while the cylindrical screen rotates continuously. Flexography comes from fast speed printing for packaging and relies on several rollers to bring the desired amount of ink with the right pattern on a substrate. The final roller, with a rubbery sleeve in which the designed pattern has been created in the form of shallow depressions and protrusions, transfers ink at a high speed onto the substrate. Important progress on these technologies were reported at the workshop, including the demonstration of a 9 cells mini-module made with full size solar cells metallized with rotary screen printing and the installation of a demonstrator inline system incorporating both rotary screen and flexographic printing units to enable ‘real life’ high-throughput experiments [18, 19].

PLATED METALLIZATION

A major alternative to screen printing that has been considered for a long time is plating. In particular Cu plating is attractive because of the much lower cost of Cu compared to Ag and the possibility to reach extremely low linewidth in combination with laser opening of dielectric layers. Whereas during the 8th MIW research efforts on Cu plating approaches appeared to have decreased in intensity, that trend clearly seemed reversed at the 9th workshop, and many new results were presented. This enhanced focus on plating is probably due to several reasons. First, the global crisis in 2020 caused Ag price to jump from about $500/kg to about $800/kg, shifting the relative cost balance between Ag screen printing and Cu plating more favorably towards the latter. More fundamentally, with the growing understanding that solar is to be deployed at a Terawatt scale in the coming decades, there comes an awareness that Ag production simply will not be able to meet the demand of the industry and that an alternative needs to be developed in time [20]. Finally, the emergence of SHJ cell mass production leads to the need for a strongly decreased cost of metallization, which is difficult to achieve with low temperature pastes because of a comparatively high paste consumption. Cu plating is a solution that can potentially drastically reduce cost of those cells while squeezing additional efficiency gains.

A major challenge for Cu plated metallization of SHJ cells is to create a seed layer with fine line pattern in a cost-effective way. Different approaches were presented. Among them, a promising new approach was demonstrated, consisting of printing a Cu-paste as seed grid, depositing a thin dielectric layer on the whole surface, and then applying electroplating which results in the growth of Cu fingers in the areas where the seed had been printed [21, 22]. Very encouraging results were also obtained with another approach where a thin sacrificial Al layer with its native oxide is used as plating mask. This layer is patterned by inkjet printing an etching aqueous NaOH solution. Cu plating is then carried out simultaneously on both sides in a bifacial plating system. Optimization and upscaling of this concept has led to full-size high-efficiency solar cells with fill factors above 81% [23].

These advanced plated metallization techniques may find application in other ultra-high efficiency solar cell concepts, such as TOPCon solar cells, as it avoids some challenges encountered when trying to apply screen printing to passivated contacts. At the workshop, the outcome of a careful optimization of a metallization sequence (including laser patterning and two plating steps) for plated bifacial TOPCon solar cells was presented. Full area solar cells with fill factors up to 81.4% and efficiencies up to 22.7% were demonstrated [24].

Those cells achieved a very high current because linewidth was determined by laser opening of a dielectric. To achieve even narrower fingers, it would be desirable to use laser sources with narrower beam, but one reaches the limits of state-of-the art scanning laser systems. It was however shown at the workshop that it is possible to go further down in dielectric ablation width through the use of a cylindrical focusing lens. Such a lens focuses light into a line instead of a spot as shown in Figure 1. Contact openings of 3 µm width and plated finger widths of 15 µm were achieved, with low contact resistivity [25, 26].

a) b)

FIGURE 1. a) Schematic illustrating the principle of laser beam focusing using a cylindrical lens, b) simulated focused spot using cylindrical lens and input beam diameter D. Experimentally, laser spots with D = 2.6 mm and width 3 µm were obtained. These images are reproduced with the author's permission from the presentation 'Formation of thin laser ablated contacts using cylindrical lens - A novel concept using cylindrical lens as focusing lens for laser ablation of solar cells' presented by Muhammad Khan at the 9th MIW[25].

INTERCONNECTION

While for many years, improving cell efficiency was the sole reason for the fantastic performance increase of PV modules, improvements in interconnection and module lay-out have recently become at least as important. 2020 saw the further penetration of half-cell modules and multi-busbars interconnection, as well as the fast-pace introduction of modules based on large cell size (182 mm and 210 mm), and various techniques to the reduce the gap between cells leading to modules with higher power density.

The choice of optimal lay-out is a complex optimization problem. The factors at play are often non-linear (e.g. going from half cells to third cells) and have impacts across the complete design. For example, the design of a multiwire interconnection has an impact on finger spacing at the cell level. At the workshop, a modelling tool was presented that optimizes metallization, lay-out and interconnection designs simultaneously for a selected performance criterion (module power, cost/Wp, etc.) [27, 28]. This was applied to bifacial silicon heterojunction solar modules and it identified the number of busbars as key parameter to reach an optimal trade-off between module power and cost.

Multiwire Interconnection

Although most solar cells are still interconnected using flat ribbons, the share of PV modules using multiple thin wires instead is steadily growing. The multi-busbar (MBB) approach, in which the wires are connected to the solar cells using conventional soldering, is getting adopted faster than the other main multiwire approach, the proprietary Smart Wire Contact Technology (SWCT) which uses wires coated with low temperature alloy attached on a carrier foil and in-lamination soldering.

A third multiwire approach was recently proposed by imec. It also makes use of wires with low-temperature solder alloy coating, but those are interwoven with encapsulant ribbons, combining the interconnection and encapsulation into one contact foil. At the workshop, a failure mode and effects analysis (FMEA) of this type of interconnection scheme was presented [29]. It correctly identified interconnect reliability as critical area of this multiwire technology and pointed at the importance of improving solder joint behavior upon thermal cycling.

Electrically Conductive Adhesives

An alternative to soldering that is started to be used more widely is the use of electrically conductive adhesives (ECAs), mostly in shingled cells modules and in some silicon heterojunction module designs. They are attractive because of their low processing temperature, the fact that they are lead-free, and their better elastic properties than solder alloys.

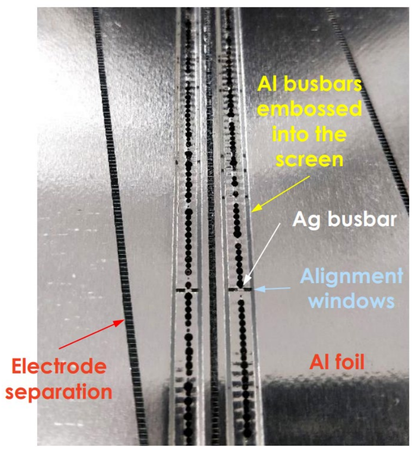
ECAs are however very expensive materials compared to solder alloys, and ECA producers are actively investigating formulations with lower silver contents. At the workshop, a study was presented in which the concept of capillary suspension was implemented in an ECA formulation [30]. The percolation threshold was achieved at an astonishingly low Ag content and first proof-of-concept shingled cells mini-modules were made.

One challenge in ECA research is to understand the impact of formulation parameters on the contact resistivity between ECA and screen-printed Ag contacts. If one applies conventional contact resistivity measurement methods without adapting them, measurement data are extremely noisy and do not contain useful information. As a result, researchers usually develop their specific lab tests that provide some relative information between samples but no absolute contact resistivity values, and comparison between measurements from different labs is impossible. A contribution at the workshop investigated the Transmission Line Method (TLM) and the TLM with Contact End Resistance (TLMCER) and explored what needed to be done in terms of test sample geometry and measurement parameters to get meaningful data [31, 32]. It was concluded that TLM and TLMCER methods can be used on ECA-based joints and guidelines for such measurements were provided.

Laser Welding of Al Foil

One of the module types in which ECAs have been used is the foil-based monolithic interconnection scheme for back-contact solar cells. The cost of this approach is however significant as, apart from the ECA, it typically also uses Cu foils integrated into the backsheet (so-called conductive backsheet technology). Recently it was proposed to replace the Cu foils by Al foils, which are very low cost, and to replace the ECA joint by a laser welded joint between the Al of the foil and the Ag of the screen printed contact that is performed after glass-glass lamination. At the workshop, progress on this approach was reported [33]. The Al foil is patterned and embossed prior to being laser welded to the cell. First one-cell glass-glass mini-modules were demonstrated with high fill factor after welding and low degradation in accelerated tests.

a)



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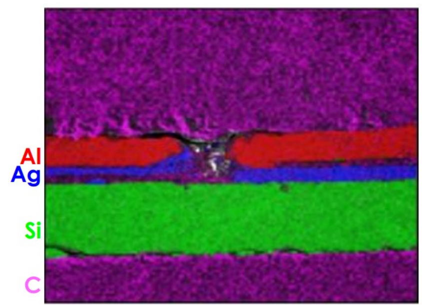


FIGURE 2. a) Photo of the back of an Al-foil + back-contact solar cell structure connected by laser welding, b) Scanning Electron Microscopy - Energy Dispersive Spectroscopy (SEM-EDS) map of the cross-section of such structure in the area of a laser-welded connection point. These images are reproduced with permission from Kathryn Fisher's presentation at the 9th MIW [33].

RESULTS OF ONLINE SURVEY

Traditionally a survey is conducted at each edition of the metallization and interconnection workshop to ask participants their views on key trends related to metallization and interconnection technologies. Due to the 9th edition being held online, a shorter version of the survey was conducted with roughly half the participants completing it. In the following the results of this online survey are presented and compared to previous survey results [34].

As shown in Figure 3, the participants anticipate that screen-printing technology will remain the dominant technology for at least another decade. Interestingly, the results for screen-printing are slightly lower than in the 2019 survey while alternative printing techniques seem to be gaining a few percentage points. Nevertheless, it is fair to say that the participants do not currently see any clear-cut alternative to screen-printing technology with the other approaches all seen as having under 10% market penetration even 10 years from now.

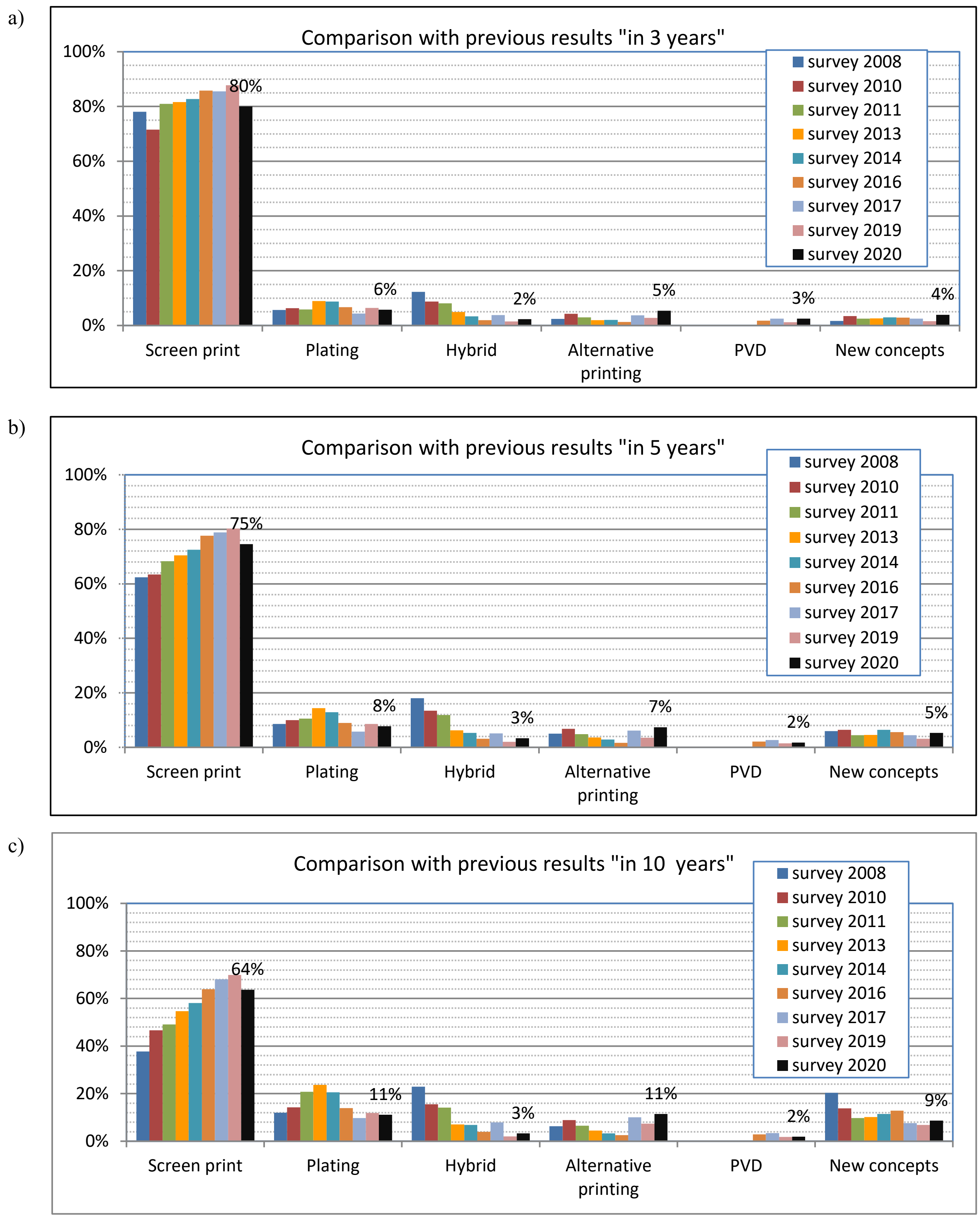


FIGURE 3. Comparison of the results to the question: "What will be the percentage share of metallization techniques in solar cell production in X years?" for all surveys in 2008, 2010, 2011, 2013, 2014, 2016, 2017, 2019, and 2020 in a) in 3 years, b) in 5 years and c) in 10 years.

In line with screen-printing being seen as the dominant technology, the participants expect that silver will remain the main metal used for the front grid metallization while copper is seen as the fastest growing alternative (Figure 4). As in previous surveys [34], the category "Other" is seen as gaining market shared indicating that the participants see the potential for other metals than silver or copper being used for the front side metallization.

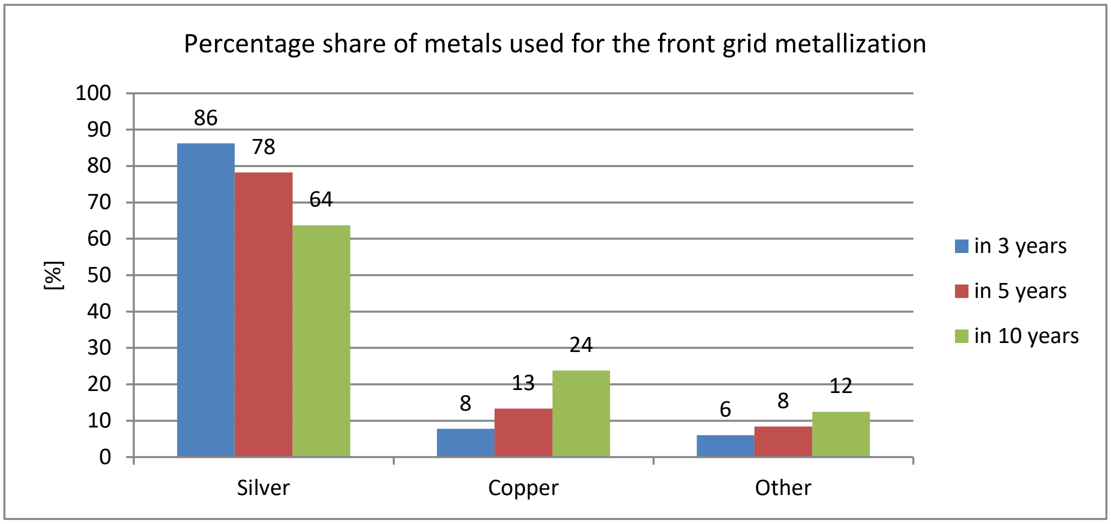
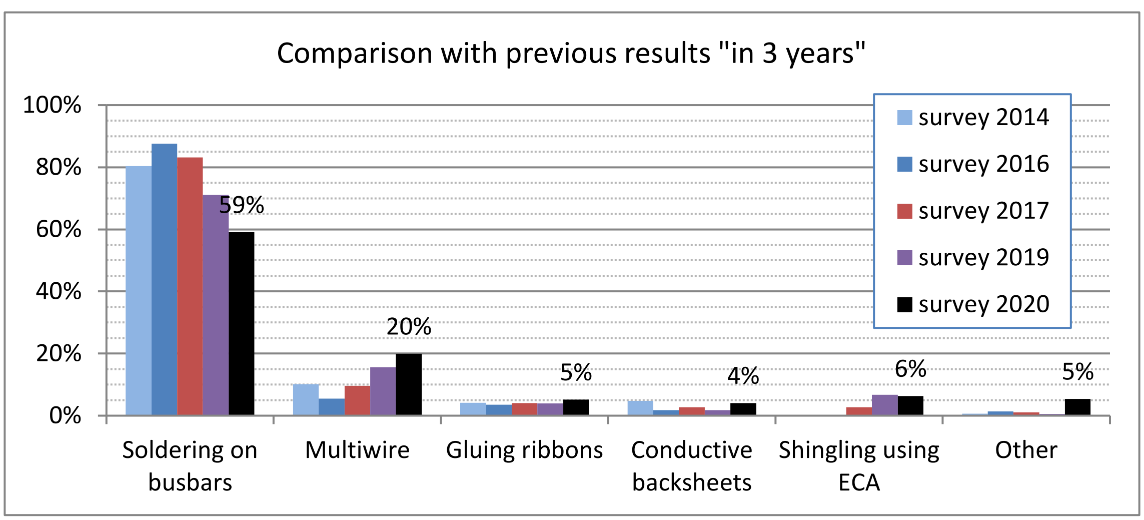


FIGURE 4. Results of the 2020 online survey to the question: "What will be the percentage share of metals used for the front grid metallization?"

Interconnection technologies are expected to diversify faster than metallization techniques. As shown in Figure 5, the MIW2020 participants anticipate conventional soldering on busbars to fall from ~59% market share in 2023 down to 35% in 2030. Multiwire technologies are anticipated to benefit the most from this with their market share expected to increase to ~29% by 2030. Other approaches such as gluing of ribbons, shingling using electrically conductive adhesives (ECA) or conductive backsheets (for back-contact cells) are also seen as potentially benefitting from the move away from soldering on busbars.

a)



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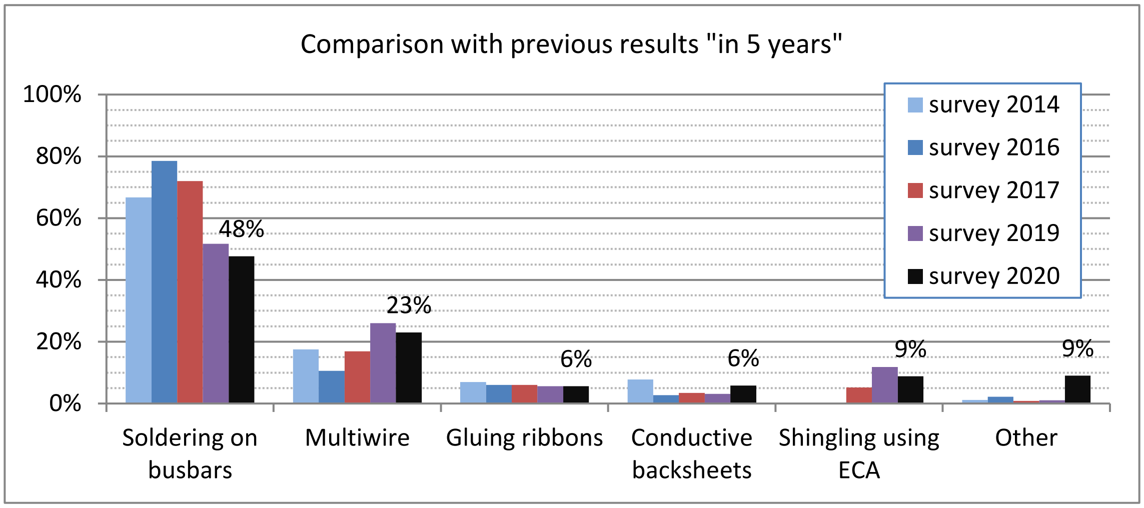

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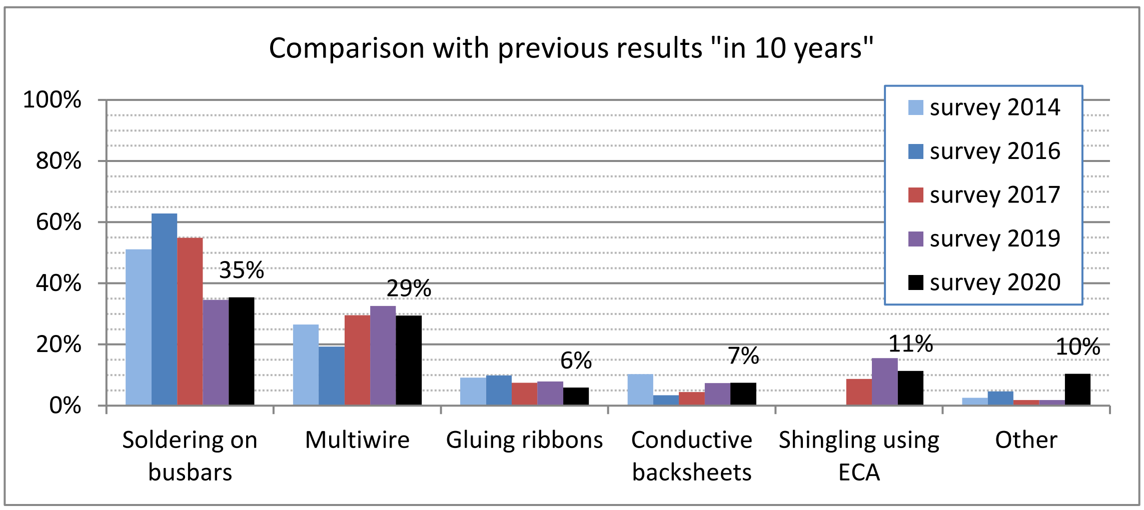

FIGURE 5. Comparison of the results to the question: "What will be the percentage share of interconnection technologies in production in X years?" for all surveys in 2008, 2010, 2011, 2013, 2014, 2016, 2017, 2019, and 2020 in a) in 3 years, b) in 5 years and c) in 10 years.

CONCLUSION

Although the 9th edition of the Workshop on Metallization and Interconnection for Crystalline Silicon Solar Cells was held as an online event, it reached the workshop goals of knowledge sharing and networking. The technology of screen-printed contacts of high temperature pastes continues its fast progress enabled by better understanding of the phenomena taking place during printing and firing, and progress in materials. However, great improvements were also achieved in low temperature paste printing and plated metallization, which have regained focus because of the nearing mass scale industrialization of heterojunction solar cells. In the field of interconnection, multiwire approaches continue their penetration enabling a better performance optimization of PV modules, but research continues on ECAs and foil-based approaches to enable the interconnection of advanced solar cell concepts. Common to many contributions at the workshop was the use of advanced laser processes to improve performance or throughput.

ACKNOWLEDGMENTS

We thank ISC Konstanz for the great support in the organization of the workshop, in particular Radovan Kopecek, Nicola Voigt, Petra Hoffmann, and Dominik Rudolph. We are grateful to the presenters and authors for their contributions at the 9th Metallization and Interconnection Workshop, and also the participants for their active involvement. Our gratitude also goes to the sponsors for making this Workshop again possible. Further, we would like to thank all members of the Scientific Committee for their involvement in ensuring a high scientific quality of the Workshop: Aba Ebong, Alison Lennon, Andreas Schneider, Antonin Faes, Evert Bende, Giso Hahn, Gunnar Schubert, Guy Beaucarne, Jan Lossen, Jörg Horzel, Jonas Bartsch, Joo-Youl Huh, Loic Tous, Pietro Altermatt, Richard Russel, Samuel Harrisson, Shubham Duttagupta, Thomas Buck.

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