Presented at the 41st European Photovoltaic Solar Energy Conference and Exhibition, 23-27 September 2024, Vienna, Austria

CHALLENGES FOR SOLDER INTERCONNECTION PUSHED BY HIGH-EFFICIENCY SOLAR CELL DEVELOPMENTS

Benjamin Grübel, Angela De Rose, Achim Kraft
Fraunhofer Institute for Solar Energy Systems ISE
Heidenhofstr. 2, 79110 Freiburg, Germany

ABSTRACT: The solder interconnection to connect solar cells in series is a key process for the manufacturing of reliable high-performance solar modules. The fast development of the cell technologies, interconnector number and the throughput requirements by industrial production lines underlines the necessity of detailed evaluation of the process challenges. Within this work, the developments of the solar cell metallization are addressed by precise evaluation of the metallized area available for the solder joint. The soldering of round wire interconnectors onto small area pads or even directly onto the contact fingers for busbarless designs reveals to become challenging for precise handling and interconnector alignment. Drastic reduction of the size of the solder pad area to realize silver reduction results in poor mechanical and electrical quality of the solder joint. Every cell technology features requirements when it comes to soldering temperatures according to sensitive layers. Therefore, we present the solder alloys available according to their melting temperature. Concerning the criticality of materials potential lead-free alloys are presented. We performed soldering processes with PERC, TOPCon and SHJ solar cells at an industrial stringer machine to evaluate temperature homogeneity of the process. A temperature discrepancy of at least 14 K for SHJ and up to 90 K for PERC solar cells was measured on the cell during interconnection. The challenges and increasing sensitivities arising from developments on solar cell level reveal the need of constant evolution of the soldering tools as well as of the soldering processes.
Keywords: Interconnection, High-efficiency solar cells, Soldering, Stringer

1 INTRODUCTION

In recent years, the PV industry has undertaken significant advancement in the development of new solar cell technologies. While the passivated emitter and rear cell (PERC) technology has dominated the market for years, it is expected to be replaced by technologies with improved performance. Tunnel oxide passivated contact (TOPCon) [1] and silicon heterojunction (SHJ) [2] solar cells are the technologies which are candidates as successor to the PERC technology [3, 4]. Even though the implementation of these new technologies into module application is at its beginning, the effort to develop the subsequent solar cell technology is already intensified. Currently solar cells based on tandem designs are estimated as next step due to their improved behavior in absorbing the light spectrum in a more efficient way [5]. Specifically, tandem solar cells consisting of at least one perovskite absorber are widely investigated in the PV community, which can be deduced by the significant increase in publications on this topic [6].

Apart from the exact solar cell technology, other developments are taking place, influencing module integration. First, optimization of wafer dimensions (size, thickness) [3] affect cell handling, hardware size of tools, industrial throughput and number of busbars/wires. Furthermore, the development of the metallization of the solar cells is driven by to main targets: efficiency and costs. In terms of efficiency, optimization of the metallization focuses on reducing the shaded area while minimizing the resistive losses. A significant drawback here is that state-of-the-art screen-printing metallization for TOPCon and SHJ require a higher amount of silver (Ag) [7] compared to PERC. However, several publications revealed the criticality of Ag facing upscaling targets of a worldwide terawatt PV production [7, 8].

The developments on solar cell level result in more a less sever challenges when implementing into module application to fabricate high-performance long-term stable PV modules. Constantly evolving manufacturing tools and processes are evident to meet this challenge. In this work, the main challenges faced by interconnection process via soldering are identified and evaluated.

2 DEVELOPMENTS OF SOLAR CELL METALLIZATION AND INTERCONNECTION PROCESSES

2.1 Developments of solar cell metallization

Solar cell technologies are constantly evolving. For the soldering process the metallization of the solar cells is essential for a reliable interconnection. Concerning TOPCon and SHJ solar cells several developments of the metallization have taken place over the last years. Both cell technologies require metallization pastes with high Ag content resulting in an increased Ag consumption compared to PERC solar cells [3, 7]. Consequently, the finger geometry is constantly diminishing while the number of busbars and therefore interconnectors is increasing to compensate the resistive losses of the fingers [3]. Furthermore, busbarless metallization layouts are arising lately to reduce Ag consumption even more requiring adapted interconnection technologies.

Concerning more sensitive solar cell technologies such as SHJ and perovskite-silicon tandem solar cells, featuring temperature sensitive layers, low-temperature metallization pastes are used. These pastes typically show reduced wetting behavior and low mechanical adhesion to the solar cell surface [9, 10].

2.2 Interconnection processes

Lately several geometrical changes of the solar cells have taken place related to format and thickness of the wafers. The increased size of the Si wafers up to 210 mm edge length requires the interconnection of a larger area with more joints to be soldered simultaneously. Therefore, temperature homogeneity during the IR soldering process becomes challenging. The selection of interconnectors for modules has drastically changed regarding the geometry from flat band to round wire with increasingly smaller diameter as the optical properties have shown to be beneficial [11, 12]. These changes require adaptation of stringer tools to be able to process and handle the solar cells as well as the new thin interconnectors. Besides being able to process, other aspects such as precision and alignment combined with high throughput are common challenges.

At this point, PV application remain excluded from the current European RoHS (restriction of hazardous substances) [13]. Consequently, lead-based solder alloys are still preferred especially due to their performance and cost advantages. Nevertheless, it is expected that the exclusion of the RoHS might be withdrawn at some point in the future, which makes it indispensable to anticipate the development of lead-free solder alloys. Alternative lead-free interconnection processes such as Ag-based electrically conductive adhesives (ECAs) are already available, even though this technology is currently quite cost-intensive [14]. Several publications have already shown that lead-free solder alloys can be suitable for PV application but especially the long-term stability plays a significant role [15, 16]. Furthermore, since soldering requires the use of solder fluxes to activate the metal surface, the chemical stability of the solar cell can be questionable. Therefore, the selection of suitable solder fluxes is evident.

3 RESULTS & DISCUSSION

3.1 Metallization area for soldering

So far soldering of solar cells requires metallic surfaces to contact solar cells mechanically and electrically. This means that only the metallization of solar cells is available as interconnection surface. We evaluated the trend of the available metallized area of different solar cell types by analyzing around 100 technical datasheets of solar cells (PERC, TOPCon, SHJ) from 2014 to 2023. In **Figure 1**, the estimated area available for the soldering process is shown in accordance with the number of busbars on the solar cell. As the formats of the solar cells is not identical (M6 – M12) for all datapoints, the area is normalized to short current density J_{sc} of 40 mA/cm². Two clouds of data points can be distinguished between solar cells with continuous full busbars (59 ± 7) mm² and solar cells with busbar consisting of a narrow line with dedicated pads (6.9 ± 1) mm² for the interconnection to reduce the silver consumption of the busbars. It becomes clear that for solar cells with pads, the available area for the solder interconnection is almost a magnitude lower than for solar cells with full busbars. The average pad size is in the range of (0.9 ± 0.1) mm for the width and (0.7 ± 0.2) mm for the length. Furthermore, even though the number of busbars is increasing from 6 to 18, the estimated area remains almost constant in a range between 30 mm² – 90 mm² with a minimum single pad size of 0.5 mm². Another trend is the increasing number of busbars for TOPCon and SHJ compared to PERC. A third data cloud belongs to busbarless solar cells depicted by the violet area. Even though these solar cells technically feature no busbars, they are interconnected with a dedicated number of wires. Therefore, the depicted area shows the estimated area for soldering for 50 fingers on a half cell with a variation of number and diameter of the wires (6 – 20 wires, 0.20 mm – 0.35 mm) and the finger width (10 µm – 40 µm). Independently of the exact configuration, busbarless solar cells have an estimated solderable area an order of magnitude lower than solar cells with busbars.

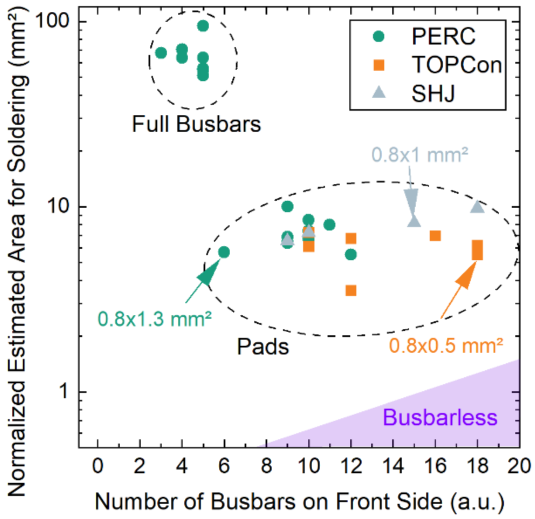

Figure 1: Normalized estimated area available for soldering depending on the number of busbars on the solar cell front side. As the solar cell format of the data points ranges from M6 to M12 the area is normalized to J_{sc} of 40 mA/cm².

The drastic reduction of the metallization area from full busbars to pads or even to busbarless solar cells shows the significant increasing challenge to provide a reliable interconnection in term of mechanical and electrical performance.

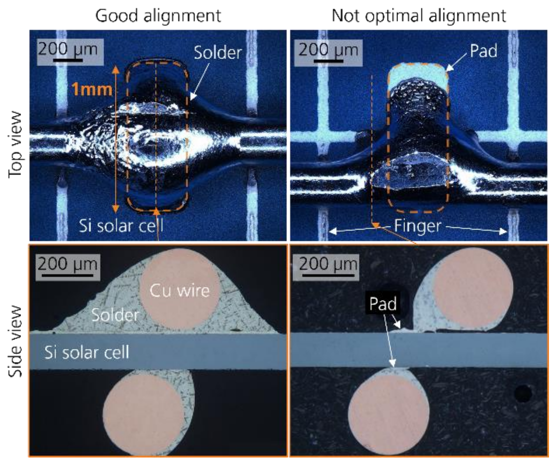

Figure 2: Top view and cross section microscopy images of soldered wires (0.32 mm) onto metal pads (width 1 mm) of a solar cell with good and not optimal alignment.

A second challenge addresses the interconnection process with industrial stringer tools. As shown in **Figure 1**, pads widths are already reduced to 0.8 mm and the wires show a trend to diameters well below 0.3 mm [3]. This requires a high level of alignment precision to solder the wires onto the pads, simultaneously on cell front and rear side. In **Figure 2**, top view and cross section microscopy images of soldered wires onto metal pads are shown. The images on the left show that the wire is perfectly aligned onto the pad, while the right image shows a clear misalignment to one side of the pad. The dimensions of wire (0.32 mm) and pad width (1 mm) shown here are rather conservative so that the precision of the wire deposition is sufficient for this case. However, it is expected that concerning the trends heading to smaller wires and pads due to material savings, such inaccuracies might lead to missing interconnection of some pads and therefore to a decreased fill factor inside the module. Furthermore, the alignment on front and rear side to each other is also important. In the cross-section image of **Figure 2**, a misalignment on the right side shows that in the worst case the wires are fully displaced to each other. This tends the risk of an uneven mechanical stress onto the solar cell which might result in cell breakage at this point.

3.3 Interaction between metallization paste and solder alloy

For a high-quality solder joint, the interaction between metallization and solder alloy has to be considered. In case of an optimized interface, the joint will be mechanically and electrically stable. Characteristics of an ideal interface are:

- Good wetting of metallization pad with liquid solder
- No damage of metallization pad by solder (*e.g.* by Ag leaching)
- Formation of a diffusion zone with limited thickness
- Formation of Ag_3Sn phase with defined thickness within diffusion zone
- Absence of voids, cracks and flux inclusions

These characteristics can be influenced by density, composition and roughness after screen-printing of the metallization paste as well as solder alloy composition, melting point, amount and type of flux and process parameters (temperature, time) during soldering. **Figure 3** shows an example of such an ideal joint.

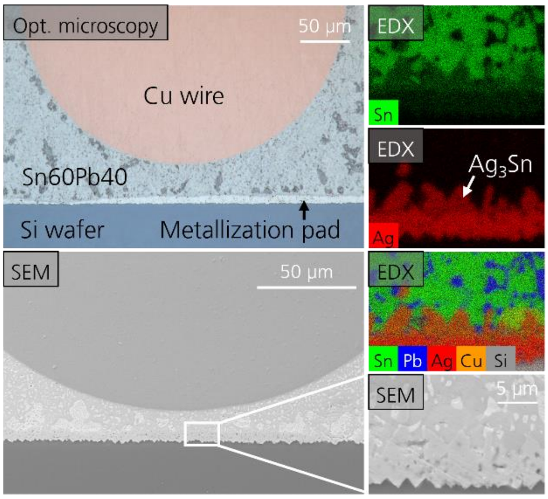

Figure 3: Cross section images of an ideal solder joint on a silicon solar cell. A diffusion zone and Ag_3Sn phase formation is found at the void-free interface between metallization and solder.

With the trend of Ag-reduced metallization, the pads become smaller but also thinner. This could influence the interface quality as well as the resulting solder joint. **Figure 4** shows an example of a joint on a very thin Ag pad. The diffusion of Sn and Ag at the interface leads to partly complete dissolution of the Ag pad in the Sn matrix of the solder, resulting in a direct contact between Sn60Pb40 and Si wafer. This leads to impeded string handling, a reduced mechanical stability < 0.2 N (90° peel force) and a reduction of the fill factor *FF* of the module due to an increased series resistance R_s.

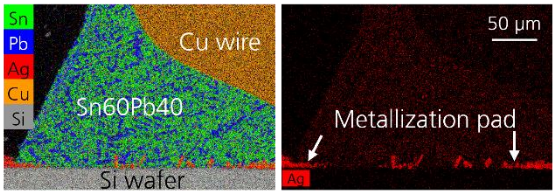

Figure 4: EDX cross section images of a solder joint on a very thin Ag pad on a Si solar cell. During soldering, Ag dissolves in the Sn matrix of the solder, leading to dissolution of the pad.

3.2 Solder alloys

So far, soldering and precisely the use of lead-based solar alloys, represents the state-of-the-art interconnection process [3]. Currently, the exception of PV applications to use lead in accordance with the RoHS is still in place. However, for the case that the exception is withdrawn, lead-free interconnection processes are required.

Figure 5 shows the liquidous temperature T_m of more than 125 different solder alloys according to the base component of each alloy on the *x*-axis. The blue horizontal dotted line represents $T_m = 183$ °C for the standard Sn60Pb40 solder alloy as reference. Furthermore, a minimum temperature of 90 °C is suggested according to IEC 61730 - 1 [17] as maximum operating temperature of conventional solar modules [17], even though even higher temperature up to 110 °C are mentioned by Kempe *et al.* [18]. A maximum temperature range up to 300 °C is defined, considering the increasing thermomechanical stress induced by large temperature differences during the cooling phase after soldering. With respect to SHJ and Si tandem solar cells, which feature temperature sensitive layers, the use of Ga-, In- and Bi-based solder alloys allows soldering processes at temperature much lower than for Sn60Pb40. Ga-based solder alloys can be treated as special case since they feature $T_m < 50$ °C and might be liquid even at room temperature. In- and Bi- based solder alloys have a broader range of T_m featuring lead-containing and lead-free alloys. The greatest amount of solder alloys is based on Sn. As can be seen, the lead-free Sn-based alloys are located, on average, at higher T_m compared to lead-containing Sn-based alloys. Solder alloys based on Pb or Au have the highest T_m of the shown material combinations.

Figure 5 involves largely all solder alloys available for different applications. However, not all of them are commercially available as research tends to take place at an academic level. For PV application, the solder alloys must fulfill several criteria such as sufficient and long-term reliable mechanical and electrical interconnection within the operation conditions without damaging the solar cells, as well as its availability for scalable purpose while being cost effective. Alloys based on Ga as main component are not suitable apart from its limited availability, due to its very low T_m, which might be beneficial only for very few applications. For In- and Au-based alloys the most critical aspect is presumably the increased material costs. However, for the interconnection of temperature-sensitive solar cells, In would allow low-temperature lead-free solder alloys. Alternatively, Bi-based alloys can be selected. When addressing lead-free soldering for solar cell technologies which tolerate higher soldering temperatures, such as TOPCon, numerous Sn-based Pb-free solder alloys are available. Especially, Pb-free solder alloys used in electronic industry are well known and evaluated due to the RoHS restriction in this industry.

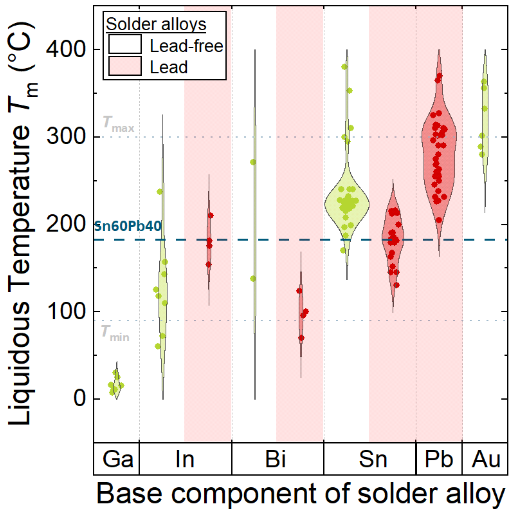

Figure 5: Liquidous temperature T_m of different solder alloys according to the main alloy component and divided between solar alloys containing lead and lead-free alloys.

3.3 Soldering Temperature Homogeneity

To ensure good wetting of the solder during the interconnection process and a stable solder joint, the soldering profile within the stringer has to be adjusted carefully. Both, soldering time and maximum soldering temperature influence the joint formation as well as mechanical stresses induced during cooling due to CTE differences between Cu wire and Si wafer [19]. The development trend towards larger wafer sizes requires homogeneous soldering over a larger area. To realize this, the IR heating lamps have been modified in stringer tools in the past years. A precise temperature control during the process is challenging but necessary due to smaller process windows for the interconnection of high-efficiency solar cells. On the one hand, the soldering temperature has to exceed the liquidus temperature of the solder alloy (183 °C for Sn60Pb40) by about +50 K, on the other hand high temperatures (and long soldering times) might damage layers within SHJ and tandem solar cells [20, 21] and promote the leaching of the metallization.

We performed in-situ temperature measurements on an industrial stringer during IR soldering of different industrial M6 half cells. The temperature is recorded at six different positions on the solar cell front side by thermocouples with a measurement uncertainty of ± 3 K. Each temperature measurement *i.e.* soldering process is repeated for at least six times to determine the statistical error, which is in the range of ± (2-7) K. **Figure 6** shows the deviation of the mean measured peak temperature T_{peak} from the set-temperature for soldering PERC, TOPCon and SHJ solar cells. The set-parameters of the soldering profile are kept the same. **Figure 7** shows the mean value of each measurement position for each solar cell technology with its standard deviation. Under consideration of both systematic and statistical error, it can be clearly seen that the temperature distribution is not homogeneous over the whole solar cell. We determined temperature differences of ΔT_{PERC} = 58 K, ΔT_{TOPCon} = 43 K and ΔT_{SHJ} = 37 K, which have to be considered respectively to not damage *e.g.* the passivation of the SHJ cell. This difference over the wafer is expected and due to the symmetry of the used hardware (IR lamps, downholder etc.) within the heating zone of the stringer.

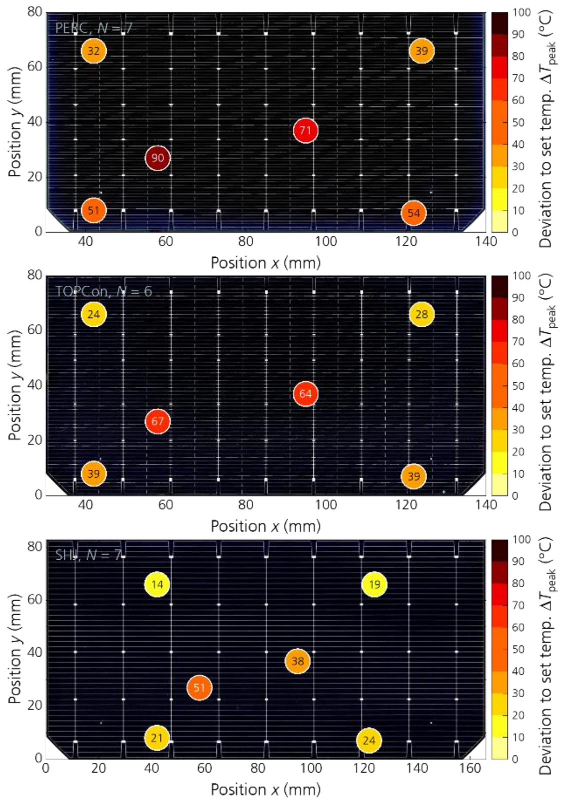

Figure 6: In-situ temperature measurement during IR soldering. Deviation of the measured mean peak temperature T_{peak} to the set temperature of soldering industrial PERC (top), TOPCon (middle) and SHJ (bottom) solar cells.

The measured peak temperatures are directly related to the emissivity of the solar cell. For higher emissivity of the cell (*e.g.* for SHJ), reflections of the IR light are lower (absorption is higher in the relevant wavelength range) and the temperature difference to the set-value is lower [22]. These results of the in-situ temperature measurement are in line with simulations by finite element modelling (FEM), published recently [23]. The FEM model computes the temperature homogeneity during the soldering process and can be used to precisely evaluate an optimal soldering temperature for any type of solar cell.

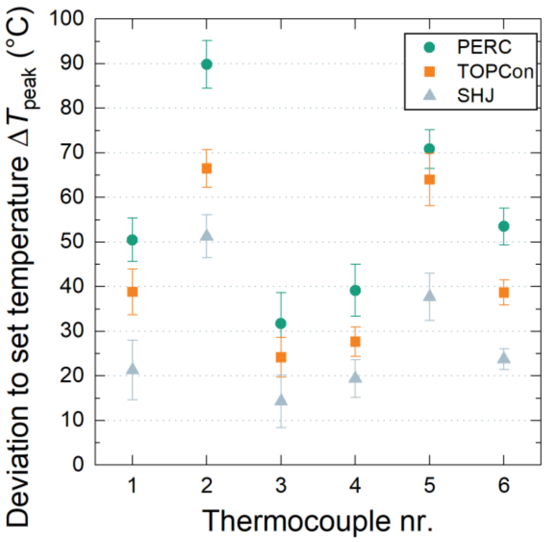

Figure 7: Measured peak temperature of solar cells at six different positions during IR soldering in an industrial stringer. Mean and standard deviation over min. 6 repetitions is given.

4 CONCLUSION & OUTLOOK

In the PV sector, ongoing developments on solar cell and module technology necessitate continuous process optimization to enhance performance while minimizing the costs.

In this work, we focus on the influence of current developments onto the interconnection process using soldering to identify and evaluate process challenges. The transition from PERC to TOPCon and SHJ solar cells has increased the amount of Ag used for the metallization. This results in metal grids with smaller fingers and busbars with an increase of the number of busbars. Larger, thinner wafers and reduced wire sizes demand precise handling and alignment increasing the challenges for the soldering process. Notably, material savings within the metal grid, especially the height of the pads, can negatively affect the quality of the soldering joint resulting in poor mechanical and electrical properties.

While Sn60Pb40 remains a reliable solder alloy for PV application. The shift to lead-free alloys is essential due to possible upcoming of changes to the RoHs directive. Various lead-free solder alloys are suitable for high-temperature applications, whereas low-temperature applications like SHJ or silicon tandem solar cells featuring temperature sensitive layers, have limited options involving Ga, In, or Bi as base component. Especially for these solar cells, precise soldering temperatures are crucial to prevent degradation. However, industrial stringer tools with IR lamps show significant temperature inhomogeneities (14 K to 90 K difference), posing risks to temperature-sensitive solar cells. Therefore, achieving a more uniform temperature distribution during soldering is indispensable.

Given the ongoing evolution on solar cell and module level, our institute will continue to focus on developing interconnection processes and tools.

5 ACKNOWLEDGEMENTS

The author would like to thank all involved colleagues for their support.

The activities have been financially supported by the German Federal Ministry for Economic Affairs and Climate Action withon the research project “Quelle” (FkZ: 03EE1172E)

REFERENCES

[1] F. Feldmann, M. Bivour, C. Reichel, M. Hermle, and S. W. Glunz, “Passivated rear contacts for high-efficiency n-type Si solar cells providing high interface passivation quality and excellent transport characteristics,” *Solar Energy Materials and Solar Cells*, vol. 120, pp. 270–274, 2014.

[2] Hao Lin, Miao Yang, Xiaoning Ru, Genshun Wang, Shi Yin, Fuguo Peng, Chengjian Hong, Minghao Qu, Junxiong Lu, Liang Fang, Can Han, Paul Procel, Olindo Isabella, Pingqi Gao, Zhenguo Li, and Xixiang Xu, “Silicon heterojunction solar cells with up to 26.81% efficiency achieved by electrically optimized nanocrystalline-silicon hole contact layers,”

[3] VDMA, “International Technology Roadmap for Photovoltaics,” no. 14. Edition, 2023.

[4] China Photovoltaic Industry Association (CPIA), “Photovoltaic Industry Development Roadmap of China,” 2023.

[5] Z. Yu, M. Leilaeioun, and Z. Holman, “Selecting tandem partners for silicon solar cells,” *Nat Energy*, vol. 1, no. 11, 2016.

[6] M. Dawson, C. Ribeiro, and M. R. Morelli, “A Review of Three-Dimensional Tin Halide Perovskites as Solar Cell Materials,” *Mat. Res.*, vol. 25, 2022.

[7] Y. Zhang, M. Kim, L. Wang, P. Verlinden, and B. Hallam, “Design considerations for multi-terawatt scale manufacturing of existing and future photovoltaic technologies: challenges and opportunities related to silver, indium and bismuth consumption,” *Energy Environ. Sci.*, vol. 14, no. 11, pp. 5587–5610, 2021.

[8] P. J. Verlinden, “Future challenges for photovoltaic manufacturing at the terawatt level,” *Journal of Renewable and Sustainable Energy*, vol. 12, no. 5, 2020.

[9] A. De Rose, D. Erath, T. Geipel, A. Kraft, and U. Eitner, “Low-temperature soldering for the interconnection of silicon heterojunction solar cells,” in *Proceedings of the 33rd European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC)*, Amsterdam, Netherlands, 2017, pp. 710–714.

[10] A. De Rose, T. Geipel, D. Erath, A. Kraft, and U. Eitner, “Challenges for the interconnection of crystalline silicon heterojunction solar cells,” *Photovoltaics International*, vol. 40, pp. 78–86, 2018.

[11] A. Protti, A. Welpulwar, J. Shahid, M. Mittag, A. Tummalieh, and C. Reichel, “Analysis of Optical Coupling Gains from Cell Interconnection for the Energy Rating of PV Modules,” (en), *40th European Photovoltaic Solar Energy Conference and Exhibition*, 2023.

[12] I. Hädrich, M. Padilla, A. Jötten, M. Mundus, W. Warta, and H. Wirth, “Finger and ribbon optics for increasing module power,” in *Proceedings of the 31st European Photovoltaic Solar Energy Conference and Exhibition*, Hamburg, Germany, 2015.

[13] *Restriction of the use of certain hazardous substances, Directive 2011/65/EU: RoHS*, 2011.
[14] T. Geipel and U. Eitner, "Electrically conductive adhesives: An emerging interconnection technology for high-efficiency solar modules," *Photovoltaics International*, vol. 11, no. 21, pp. 27–33, 2013.
[15] T. Geipel, D. Eberlein, and A. Kraft, "Lead-free solders for ribbon interconnection of crystalline silicon PERC solar cells with infrared soldering," in *AIP Conference Proceedings 2156*, Konstanz, 2019, p. 20015.
[16] D. Güldali and A. De Rose, "Material Joint Analysis of Lead-Free Interconnection Technologies for Silicon Photovoltaics," in *45th International Spring Seminar on Electronics Technology (ISSE)*, 2022.
[17] *DIN EN IEC 61730-1 module safety qualification – Part 1: Requirements for construction*.
[18] Michael D. Kempe, Derek Holsapple, Kent Whitfield, and Narendra Shiradkar, "Standards development for modules in high temperature micro-environments,"
[19] L. C. Rendler, A. Kraft, C. Ebert, S. Wiese, and U. Eitner, "Investigation of Thermomechanical Stress in Solar Cells with Multi Busbar Interconnection by Finite Element Modeling," (eng), 2016.
[20] B. A. Korevaar, J. A. Fronheiser, X. Zhang, L. M. Fedor, and T. R. Tolliver, "Influence of annealing on performance for hetero-junction a-Si/c-Si devices," in *Proceedings of the 23rd European Photovoltaic Solar Energy Conference and Exhibition*, Valencia, Spain, 2008, pp. 1859–1862.
[21] J. Haschke, R. Lemerle, B. Aissa, A. A. Abdallah, M. M. Kivambe, M. Boccard, and C. Ballif, "Annealing of Silicon Heterojunction Solar Cells: Interplay of Solar Cell and Indium Tin Oxide Properties," *IEEE J. Photovoltaics*, pp. 1–6, 2019.
[22] A. De Rose, D. Eberlein, O. Parlayan, A. Kraft, and B. Grübel, "Optimized Soldering for the Transition of Industrial Silicon Solar Cells & Modules from PERC to TOPCon or SHJ," Chambéry, Apr. 15 2024.
[23] D. C. Joseph, A. De Rose, D. Eberlein, O. Parlayan, B. Grübel, A. J. Beinert, and D. H. Neuhaus, "Investigation of Temperature Homogeneity During Infrared Soldering of Silicon Solar Cells Using the Finite Element Method," *EPJ Photovolt.*, submitted 2024.