The sun is rising on conductive adhesives

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Abstract

Although electrically conductive adhesives (ECAs) have been around in the PV industry for several years in panels based on conductive backsheets as well as in the so-called *shingled* or *tiled* modules, several evolving trends and new technologies are currently converging to bring ECAs firmly into the mainstream spotlight. These include the ongoing move to thinner wafers and larger cell formats, as well as the inevitable increase in market penetration of high-efficiency concepts based on heterojunction (HJT) and silicon–thin-film tandem cell architectures. With mature product offerings now available from several of the leading industrial PV equipment and tool manufacturers, and latest-generation ECAs available from suppliers, this article aims to provide important background information on ECAs, as well as give a brief overview of some of the challenges and cutting-edge developments in ECA-related PV applications.

Introduction

ECAs in PV have two primary uses: 1) as a replacement for solder in traditional soldered applications (e.g. ribbon stringing), and 2) in other applications in which traditional solder would either not be viable (e.g. shingling) or not produce a satisfactory outcome (e.g. temperature-sensitive cell concepts). Compared to solder, the material properties of ECAs – such as their electrical conductivity, elastic modulus and thixotropy – can be very finely tuned, often over very wide ranges. The complex nature of ECA composites means that there are many more levers that experts can pull in order to craft the perfect product for a particular use, and major ECA manufacturers have been known to work closely with module producers to create tailored solutions.

A decade ago, ECAs had a reputation for being inferior to solder in regard to long-term reliability, with problems such as embrittlement, water ingress and corrosion playing major roles in this. However, recent years have seen big improvements in these and other characteristics, so much so that ECAs can now not only stand their ground against solder but also in some ways offer superior performance. Finally, despite the relatively high cost of some ECAs due to high silver content, ECAs also have the desirable characteristic of being free of toxic lead, which is particularly important for manufacturers in many regions because of ongoing developments in their respective regulatory environments.

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History

The history of the use of ECAs in microelectronics packaging goes back to the 1950s and has been summarized by Nicolics & Mündlein [1]. Over the past decades, ECAs have found widespread application in bonding silicon chips to lead frames and in the attachment of passive chips in automotive electronics, RFID tags or LED fabrication [2,3]. Other applications have been addressed in order to avoid hazardous lead in electronic devices, so that ECAs are used as promising lead-free materials for flip-chip and surface-mount attachment of devices to circuit boards [4]. A particular class of ECA, namely anisotropic conductive tape, is used for manufacturing LCDs [5].

In PV module integration the first publications on using ECAs go back to 2001 [6,7]. During the time of serious silicon supply shortage up until the mid to late 2000s, a wafer thickness reduction from around 300μm to below 180μm was forecast that would improve effective silicon usage. Driven by these concerns, ECAs gained much interest for the interconnection of very thin solar cells, in which lower thermomechanical stress after interconnection decreases cell bending and increases the fracture strength compared to soldered cells [8].

One of the first major applications of ECAs in PV modules was the integration of metal wrap-through solar cells in the conductive backsheet approach [9]. In parallel, ECAs have been used to integrate HJT solar cells in modules [10–12]. ECAs prove to be a soft and reliable method for interconnection at temperatures below 200°C. The absence of hazardous

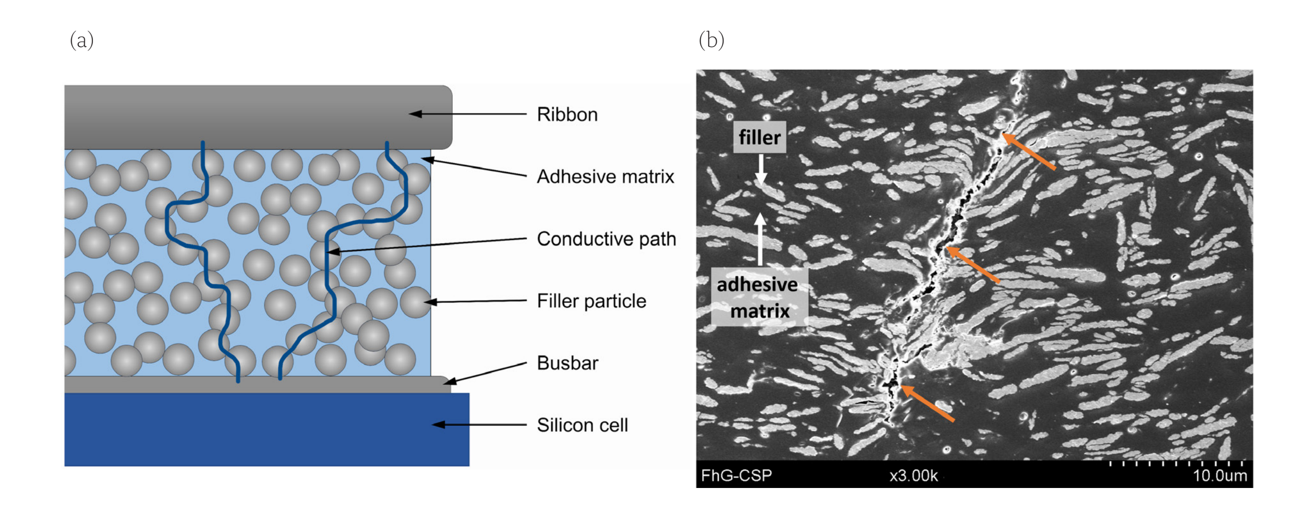

Figure 1. (a) Percolation through ECA bonds. (b) Cross-sectional SEM image showing the microstructure of ECA, with a cohesive crack marked by orange arrows.

lead is an important advantage of HJT cell and module technology. In recent years, German equipment manufacturer teamtechnik commercialized a stringer to process ECAs on an industrial scale, which ENEL in Italy and Hevel in Russia introduced into their production lines [13,14]. Since then, other leading tool makers – such as Applied Materials, Mondragon and others – have introduced their own advanced ECA stringers, and high-value advances in the technology continue to be made.

Other applications of ECAs that were introduced in the late 2000s include the connection of bus conductors of monolithic thin-film or organic solar panels, as well as shingling or ribbon interconnection of flexible thin-film solar cells [15,16]. Eventually, the shingle interconnection of crystalline solar cells gained a lot of attention in the mid-2010s when, for example, SunPower/Maxeon started to commercialize the 'Performance Series' [17]. Since then, other module manufacturers, especially in Asia, included similar products in their portfolios. For the shingle interconnection method, ECAs are a key technology, as they form mechanically flexible joints that can absorb mechanical stress.

Composition, function and characterization

ECAs are composites of conductive particles (a.k.a. *filler*) in a non-conductive adhesive matrix, wherein the conductive particles provide the required electrical conductivity, and the adhesive matrix holds the particles together and supplies the bonding strength. The adhesive is generally a heat-cured epoxy, acrylate or silicone; however, in principle any adhesive can be used, with the caveat that it must be chemically and thermomechanically compatible with the other solar cell and module materials as well as with the conductive filler.

ECAs used in PV are usually delivered as frozen, two-component mixtures of the adhesive base and a curing agent, which are thawed shortly before use and should be used completely within a period of several hours. Alternatively, they can be delivered as two separate components, which are easier to store since they do not require freezing, but dedicated on-site mixing equipment is required in this case to prepare the material for use. ECAs can be deposited at specific positions or in desired layouts on the target substrate via several means, including screen or stencil printing and pressure-time or jet dispensing, although, in practice, only screen or stencil printing are currently widely used in high-throughput production.

Unlike in bulk conductors such as solder, conduction in ECAs occurs via percolation (see Fig. 1(a)). In other words, charge is conducted between adjacent particles, and conductive pathways, consisting of chains of particles, bridge the separation between the bonded surfaces. A critical parameter in such systems is the percolation threshold, which depends on the volume concentration of particles, their shape and their three-dimensional arrangement. Below the percolation threshold, and for a given particle shape and size distribution, ECAs exhibit a relatively high resistivity which depends on the particle concentration. When the particle concentration is increased to the percolation threshold, the resistivity rapidly decreases by several orders of magnitude, and any further increases in particle concentration have little further effect on the resistivity, but can increase the ampacity. The higher the filler content, the lower the adhesion force, since the filler occupies a greater proportion of the bond interface area, displacing the adhesive.

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The primary challenge in ECA development is therefore to create a system with the lowest possible percolation threshold providing good electrical properties while maximizing the adhesion strength. For a given filler and filler concentration, the adhesive strength and other important characteristics of the cured material – such as the elastic modulus and glass transition temperature – can be improved by tuning the molecular weight(s) of the component polymer(s) and their branching ratio(s), dispersity and side chain functional groups, as well as through the addition of plasticizers and additives, and by the amount and type of curing agent. Likewise, the characteristics of the uncured material – such as the rheology, pot-life and appropriate temperature profile for curing – can be similarly adjusted.

Conductive filler particles in ECAs can be spheres, granules, rods, flakes or fibres, and may be solid or hollow. Shapes with high aspect ratios – such as rods and fibres – have a greater potential to form conductive pathways and thus yield the lowest percolation thresholds, but are also more likely to form aggregates. In contrast, higher surface area spheres tend to produce the most homogeneous composite, but require a higher concentration to reach the percolation threshold. Flakes provide an excellent balance of high aspect ratio and high surface area for interacting with the adhesive, but can also be costlier to produce, whereas granules tend to be the cheapest shape to produce.

In practice, the distributions of filler particle sizes and shapes are often closely guarded trade secrets of the manufacturers. ECA filler particles must not only be highly conductive but also be chemically compatible with the components of the adhesive matrix (both uncured and cured) and resistant to corrosion. For these reasons, silver is often used as the filler because of its relative inertness and high conductivity; however, as with much of the rest of the PV manufacturing industry, the high cost of silver, coupled with the high exposure to commodity price risk, is a strong driver in the search for alternative materials and/or material solutions. Market-available examples of such alternatives include the use of hollow silver spheres, which exhibit the same percolation threshold concentration as solid spheres but with potentially very large reductions in silver mass, as well as the use of other cheaper metals, such as copper, with a silver coating to inhibit corrosion. As the annual consumption of ECAs for PV applications increases over the next few years, we can expect to see further advances and new technology developments to meet market demands for product features and cost reductions.

ECAs can be either *isotropically conducting* (ICAs), where the material conducts equally well in all directions, or *anisotropically conducting* (ACAs), where the material conductivity is much higher in one direction than in the other. In the cured state, ICAs are generally two to three orders of magnitude more resistive than ACAs ($10^{-2}\Omega$cm vs. $10^{-4}\Omega$cm). ACAs as used in PV applications are more conductive in the *z* direction than laterally (i.e. between the ribbon and the cell in ribbon-stringed concepts, or between the two cells in shingled concepts); however, this only occurs after curing under *z*-axis compression. This means that, in addition to the ECA amount and curing temperature profile, the applied force during curing is another process lever that can be tweaked to optimize module product performance.

An understanding of the current transport for reliable and efficient ECA interconnections requires knowledge of the underlying microstructure. The microstructure can be revealed using several techniques – such as X-ray analysis, optical or electron microscopy (e.g. after the preparation of cross sections at random or specific positions) – down to (for example) the nanometre scale at defects sites.

On the one hand, the microstructure allows for the development of ECAs, a control of optimized conductive filler contents, filler shapes or filler dispersion in the polymer matrix with an impact on the resistance of the contact or thermal conductivity. The filler network microstructure and surface chemistry play important roles in the development of the conduction path. Since ECA contacts exhibit a thickness in the micron range, a microstructure analysis of contact cross sections allows a realistic insight into the actual contact geometry and ECA distribution, providing an assessment of the real contact area which is influencing the adhesion and therefore the peel force. Different production processes or material combinations can thus be quantitatively compared by microstructure analysis.

On the other hand, the impact of accelerated ageing specifically on the ECA contact can be made clearly visible in the microstructure and assigned to distinct failure mechanisms. Cross-sectional images reveal cohesive or adhesive cracks (see Fig. 1(b)), delamination, bubbles, ECA squeeze-out or structural changes (i.e. by galvanic corrosion). Furthermore, precise information about the microstructure can be used to support simulations to predict stresses and reliability.

The electrical properties of ECA-bonded joints can be sensitively probed by analysis of the contact resistance, which has a direct effect on the series resistance of modules created with ECA interconnections. Changes to the ECA bulk, or to the ECA–metallization or ECA–ribbon interface, can manifest as increases in the contact resistance long before any discernible visual changes, making contact resistance analysis a powerful tool in the improvement and optimization of ECAs and ECA bonding processes.

In interfaces between metals and crystalline or semicrystalline semiconductors, the transmission line method (TLM) (Fig. 2(a,b)) has traditionally been used to measure the contact resistance, and has a strong foundation in physical models of such systems. However, the interface between solar cell metallization and the adhesive–filler composites of which ECAs are composed is substantially different to the interfaces in those systems. Although

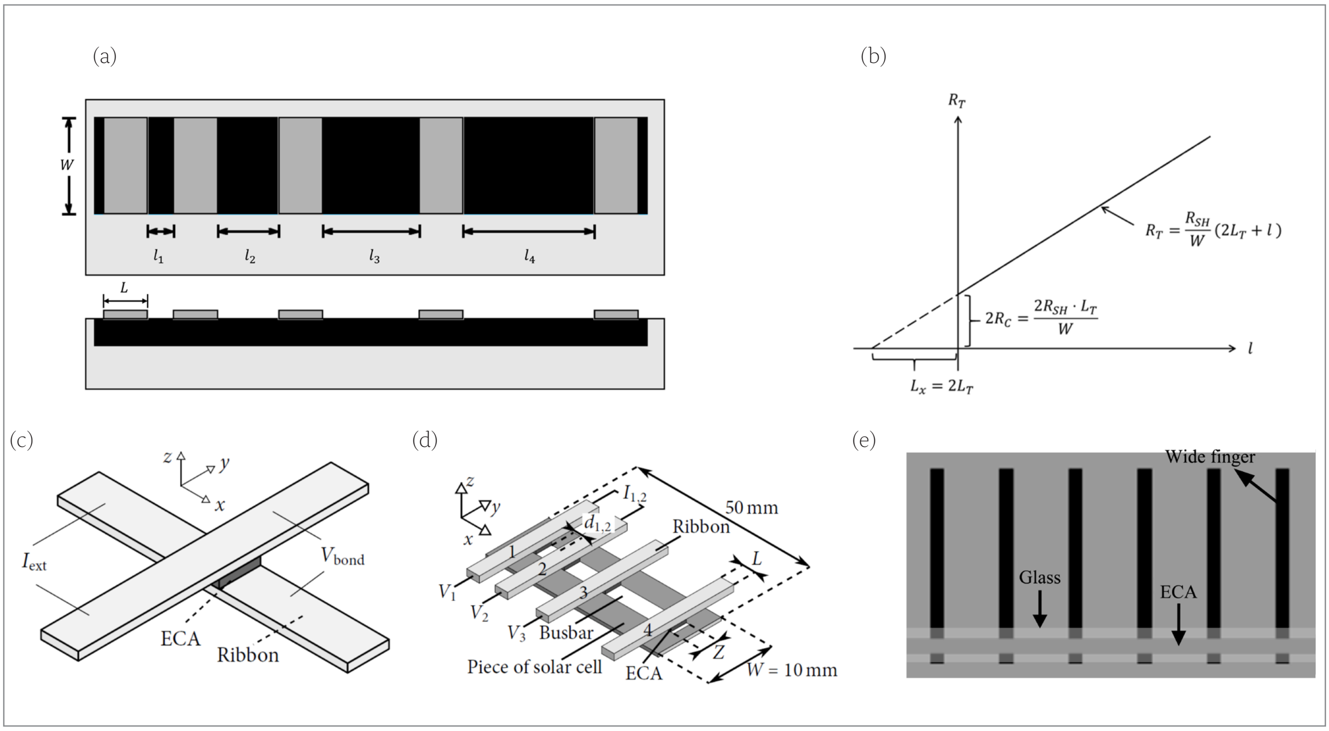

Figure 2. (a) Traditional TLM test structure [18]. (b) TLM plot for parameter extraction [18]. (c) Stacked Greek cross test structure [19]. (d) Ribbon–busbar test structure [19]. (e) Wide-finger test structure [20].

TLM can be (and has been) used to usefully track changes in the contact resistance of ECA-bonded joints through, for example, accelerated ageing tests, the objective relevance and true comparability of any values thus obtained remain unconfirmed. The actual contact area also influences the electrical performance of the contact; even though such changes can be quantitatively measured by the degradation of the contact resistance, there will be always a dependence on the contact size. For this reason, TLM can also be used to extrapolate the specific contact resistivity between adhesive and adherend, which does not depend on the size of the contact. Nevertheless, inconsistencies have been observed in the literature-reported values of contact resistivities in devices, depending on their dimensions (from nanometre in microelectronics up to centimetre scale in PV devices). The addition of ECAs as a means of contacting increases the complexity of the system and therefore also the extrapolation of the contact resistivity. Thus, efforts are currently under way to adapt the TLM methodology for ECA-based contacts (Fig. 2(c–e)) in order to extrapolate the contact resistivity of this type of joint.

Whatever characterization tools or methods are used to assess the material and interfacial properties of ECA-bonded joints, and thus improve the material characteristics and/or processing conditions, there is no substitute for extensive bill of materials (BOM) screening to avoid unanticipated chemical interactions with additives or components of the encapsulant or backsheet, as well as thermomechanical incompatibilities with the module stack. Fig. 3 shows the results of such a BOM study comparing different combinations of ECA, encapsulant and backsheet in a shingled module configuration. Stark differences in the long-term reliability of the different combinations are clearly evident.

Applications

As already mentioned, one of the earliest uses of ECAs in PV was in premium modules based on conductive backsheets. However, as the properties of ECAs have been tuned towards PV applications, the range of uses of ECAs in PV has not only grown to include high-efficiency, high-reliability concepts, such as shingling and ribbon interconnection of HJT cells, but is now beginning to encompass more mainstream and budget concepts, such as passivated emitter and rear cell (PERC)- and polycrystalline-based modules.

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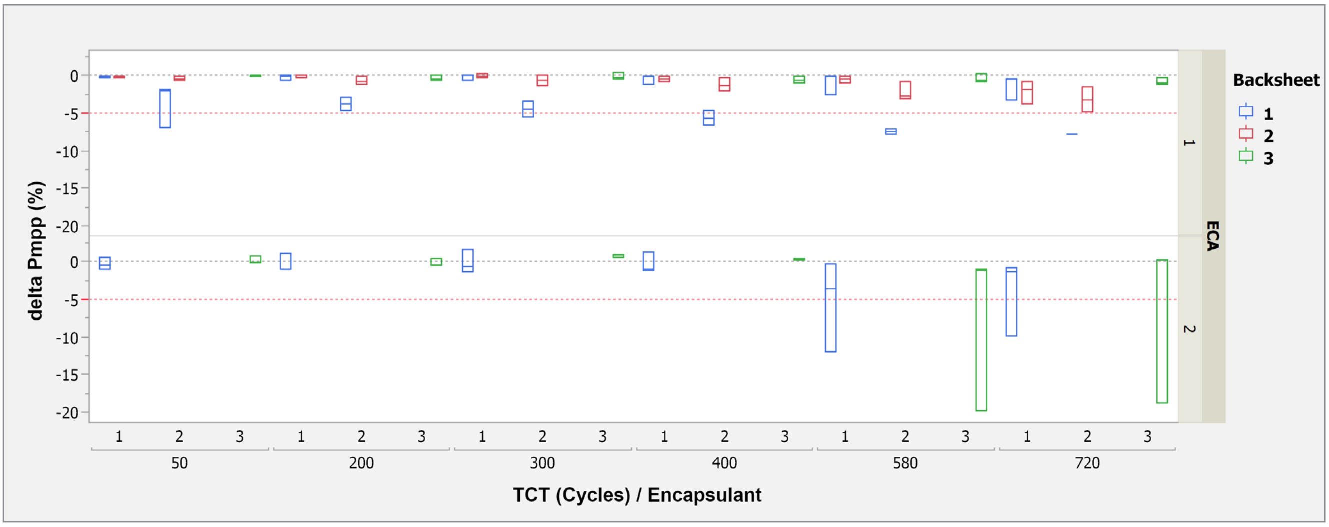


Figure 3. Comparison of different shingled mini-module BOM combinations of two ECAs, three backsheets and three encapsulants, showing stark differences in the degradation of module performance as a function of the number of thermal cycles. The grey dotted line indicates the initial power level, while the red dotted line represents the –5% pass/fail criterion as defined in IEC 61215.

Conductive backsheet

With respect to module integration, the interconnection of rear-contacted solar cells poses challenges, since classical stringing is not applicable. Excessive cell bowing after single-sided ribbon attachment can hinder automatic handling; tabber-stringers need to be specially adapted.

The conductive backsheet (CBS) approach is a dedicated interconnection technology for back-contact solar cells (mainly IBC or MWT). The Dutch company Eurotron and the ECN/TNO research centre have pioneered this alternative interconnection technology. By taking advantage of the fact that all contacts are located on the rear side, cells are interconnected by methods based on printed circuit board technology. An ECA (or solder paste) is deposited by screen/stencil printing or dispensing on either the solar cell metallization or the CBS to form local contacts between the two components during lamination. The circuit for current flow itself is a thin, patterned copper layer that is mostly laminated onto a classic PV backsheet. An insulation layer between the cells and the copper layer prevents short circuits, and, because all cell–cell interconnections are underneath the solar cells, no shading losses occur. Because the conductors are as wide as the solar cell, the thickness can typically be limited to 35μm for copper layers. Fig. 4 shows a cross-sectional image of the resulting module sandwich.

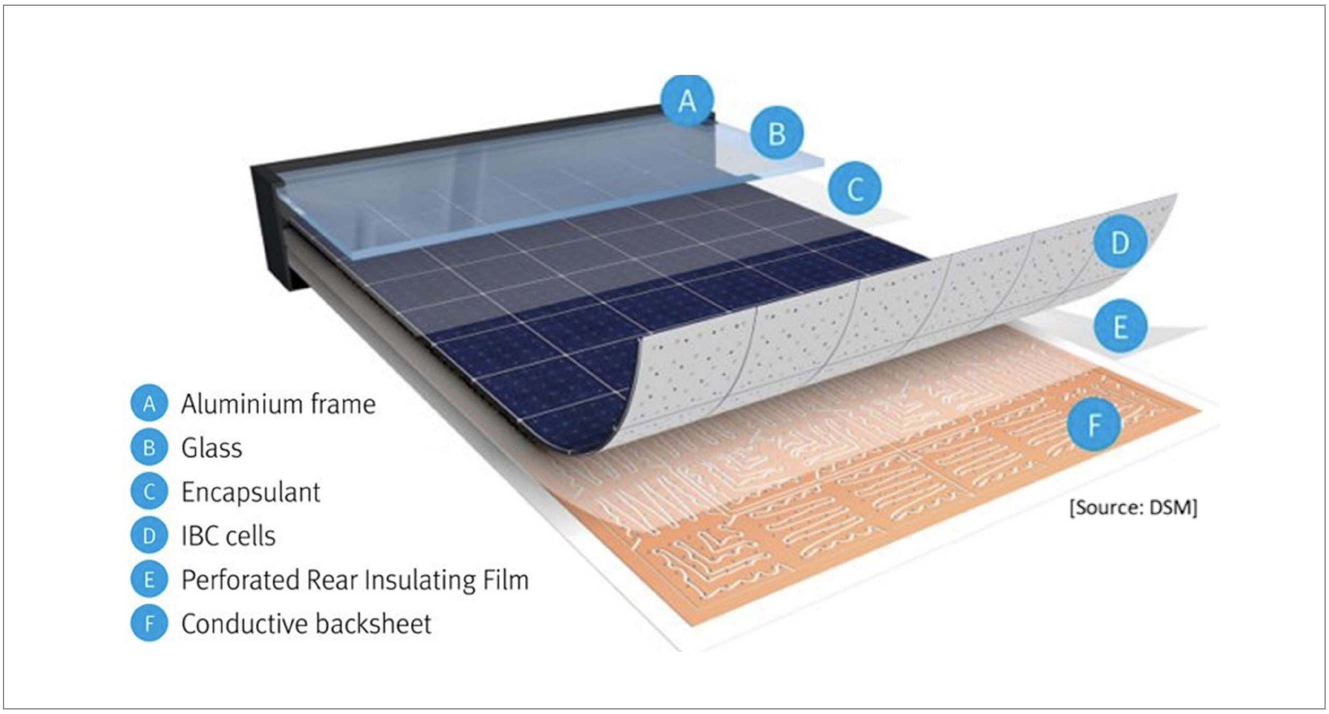


Figure 4. General structure of a CBS laminate [21]. The module is assembled from the rear to the front: first the backsheet, then encapsulant/isolation, ECA, cells, encapsulant and glass. Electrical contact between the cells and the backsheet circuit is then made by curing the ECA during lamination.

The advantages of this approach to module fabrication include low resistive power losses and a low-stress module manufacture (pick-and-place step to lay up the cells, contact formation during lamination). The full copper rear side additionally provides excellent heat dissipation characteristics that can lower the normal module operating temperature. The flexibility of the design of the circuit pattern makes CBS suitable for full, half or other cell-fraction formats and will enable the integration of active circuit elements in future applications.

CBS technology depends on small, highly conductive local contacts that need to bridge the distance introduced by the thickness of the rear insulator (typically 200μm). Hence, ECA enables this technology to work not only because of its versatile processing and high conductivity but also because of its good elasticity. The fact that ECA cures during lamination helps to overcome the bowing issues, since contact between cells and backsheet is made during lamination, and thus the laminate compensates the thermomechanical stress between the components, especially the rigid front glass plane. Additionally, the elasticity of the cured ECA mitigates residual stresses and thermomechanical stresses in the laminate that lead to joint fatigue, making CBS modules very robust against thermal expansion/contraction.

Ribbon contact / busbar replacement

The use of ECAs as solder replacement is a very attractive route in dedicated PV cell interconnections such as: HJT cells, which require processing at lower temperatures; back-contacted cells, which demand a better control of cell warpage after interconnection than in the case of two-side-contacted cells; and thin solar cells (<160μm) with a reduced thermomechanical stress budget. The

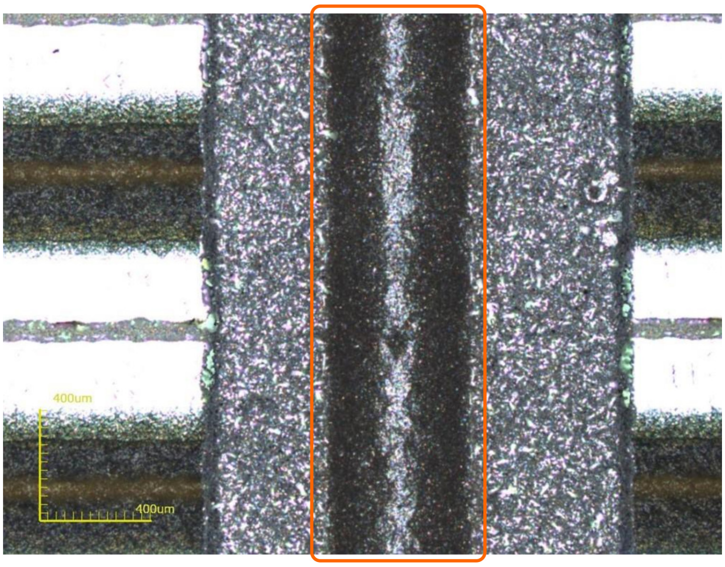
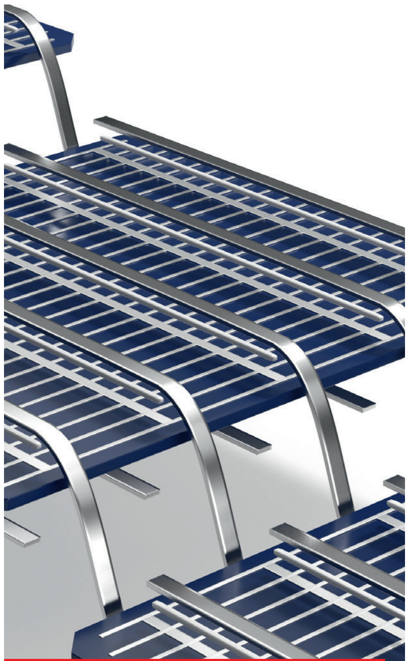


Figure 5. Light microscopy image of an IBC cell section with screen-printed ECA (dark bar within orange line perimeter) cured on a 1.5mm-wide busbar.



mechanical properties of the cured ECAs as well as their processing requirements, including curing temperatures in the range 100–170°C and curing times of usually several seconds (but up to 1–2 min for lamination-cured ECAs), address the above-mentioned process constraints.

As a case study, the interconnection of back-contacted cells ('ZEBRA' IBC cells developed at ISC Konstanz) with silver-coated copper ribbons and two commercially available, PV-specific ECAs with different polymer matrices (acrylic and epoxy) was compared to traditionally soldered reference cells [22]. Fig. 5 shows an example of the ECA line on one of the busbars. After curing of the ECA according to manufacturer specifications, the 180° ribbon peel forces obtained were around 1.15Nmm^{-1} for the ECA-bonded ribbons and 1.5Nmm^{-1} for the soldered ribbons; the cell warpage of the M2-sized cells after manual laboratory stringing was in the range 9–14mm for the ECA-bonded cells and 10–11mm for the soldered cells. By using industrial stringing units (teamtechnik TT2100 for soldering and TT1600ECA for ECA bonding), the high bowing values could be reduced by approximately 35%. This was achieved by several means, including improving the spatial homogeneity of the heat distribution over the cell, avoiding temperature overshooting, controlling the cool-down and the pressing of down-holders of the stringer during all processing steps up to and including the cool-down step.

At least double the duration of IEC standard reliability tests (IEC61215-2) could be easily sustained using glass–backsheet mini-modules (each with two half-cell strings) and EVA as encapsulation. Such modules passed 2,000h of damp heat testing (DHT, 85°C at 85% relative humidity) and 400 cycles of thermal cycling testing (TCT, –40°C to 85°C in a cycle time of 6h) with no delamination, discoloration or loss of P_{mpp} greater than 5%$_{rel}$ (tests showed a maximum 2.6%$_{rel}$ loss), confirming the compatibility with other module components and the predicted excellent long-term operation.

In the same study, voids were also observed in cross sections of the ECA joints, as shown in Fig. 6, and is a known issue for both soldering [23] and

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adhesive interconnections [24]. According to current test results, this aspect is not classified as critical; nevertheless, minimizing or avoiding these cavities would increase the performance (lower electrical resistance, higher adhesion force) and reliability of the joint. Overall, the mechanical properties of the cured ECA matrix must be able to withstand light deformations caused by thermomechanical stress, mechanical loads and common dynamic mechanical loads, such as vibrations from the surroundings.

Positive technical, processing and reliability aspects cannot alone drive a technology to mass production if the cost structure is incompatible with common market pricing per Wp. Considering current ECA material costs and rapid reductions in the adhesive quantity per interconnection, it is certainly possible to at least achieve cost parity with soldering processes while still retaining the range of benefits of ECAs. In particular, ECA-bonded joints provide a lead-free interconnection and an expected easier and more convenient recycling of PV components from ECA-bonded joints compared to soldered joints in PV panels. This means a move in the right direction with respect to the environmental friendliness of PV panels.

Despite the sometimes-perceived status of ECAs in PV as being 'under development', industrial tools have long ago moved on, with the first high-throughput ECA stringer presented to the market by teamtechnik in 2014. Since then, many trials have been performed at the company to get a deeper understanding of the ECA application in terms of applying, curing and handling, and other tool manufacturers have since launched their own versions on the market. From 2018 onwards, there have been teamtechnik TT1600ECA stringers in industrial production 24/7, and, for the near future, a continuing trend towards increased market share is assumed.

However, manufacturers of such tools have had to overcome several challenges specific to ECA

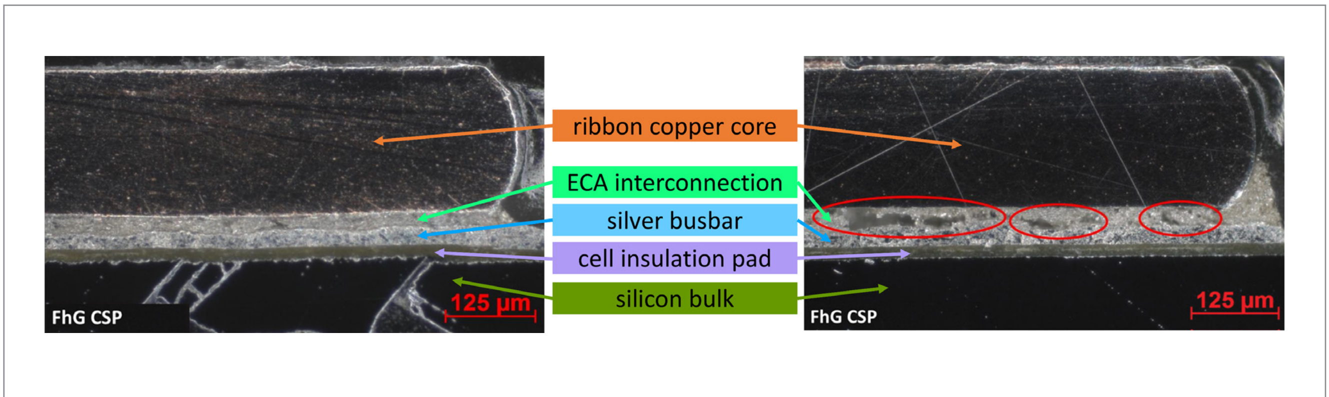

Figure 6. Cross section of an IBC 'ZEBRA' cell, with ribbon and ECA joints showing good interconnection (left), and bad interconnection (right) with voids (marked by red ellipses).

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stringing, including the requirement for high positioning tolerance of the ribbon onto the ECA print. Examples of ECA ribbon stringers such as the TT1600ECA offer the key advantages of low-stress and lead-free connections, as well as the absence of flux vapours in the machine, resulting in lower cleaning and maintenance burdens, and customers report a high level of machine availability and process stability. The high throughput of such machines, coupled with opportunities to reduce and minimize silver consumption by coordinated layouts of busbars and ECA printing, can significantly lower the cost of ownership. The use of structured ribbons – such as the light-capturing ribbon LCR™ – is also possible without any reduction in throughput. In short, the ECA stringing process is of interest for a number of cell types, including HJT, IBC, tandems and thinner PERC cells.

Ribbon-contact reliability

Only a relatively simple production equipment update is needed to achieve lead-free products. The replacement of lead-containing solder by ECA is an alternative, and standard solar cells with H-grids can be used. A direct comparison was performed, using the same solar cell type and only the solder was replaced by ECA and another ribbon (tin-free).

The long-term reliability of a product directly correlates to the quality measures used to control the manufacturing processes. In a detailed study, the curing process of the ECA was examined using standard PERC cells. Two different ECAs were investigated with different curing temperatures,

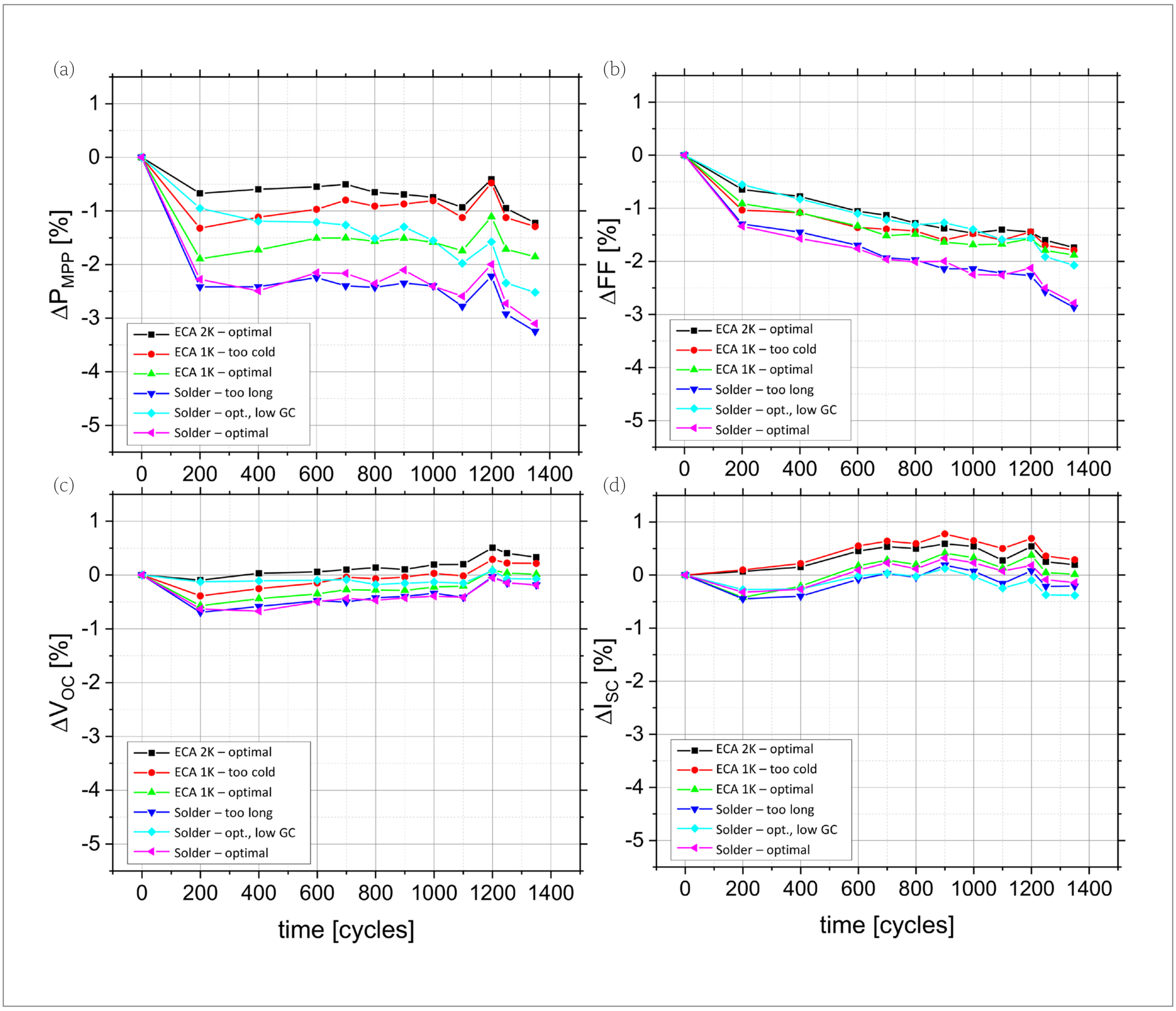

Figure 7. Trend charts of modules with 60 full cells during extended thermal cycling in accordance with IEC 61215-2 MQT 11, with different electrical contacting consisting of either two- (2K) or one-component (1K) ECAs with different process temperatures and, for comparison, soldered contacts also with process variations. (a) P_{mpp} under standard test conditions (STC), where the initial decrease is mainly attributed to LID/CID effects. (b) Fill factor, where a constant trend is visible for all modules. (c-d) V_{oc} and I_{sc}, which both remain relatively constant, indicating that the PERC cells did not internally degrade.

and these were compared with the standard soldering process. Full-size, 60-cell modules were manufactured with the same BOM, and the extended TCT results are shown in Fig. 7. Besides TCT, extended DHT (more than 2,000h) and humidity–freeze testing (HFT, more than 100 cycles) were performed. The performance of the modules fabricated using ECA was similar to that for the soldered references, with the main degradation being cell related.

After the first 200 cycles, a loss in power of 0.5–2.5% was observed, mainly attributed to the fact that the modules were not light soaked prior to the test. As a current (near I_{mpp}) is applied to the modules during the heating phase (–40°C to 85°C per IEC 61215-2), this acted as the initial light stress to induce the light-induced degradation (LID) effect per current-induced degradation (CID). Over the period of more than 1,000 cycles of TCT, no decrease in I_{sc} or V_{oc} was observed, leading to the conclusion that the PERC cell itself was very stable. During the test, a small but constant loss in fill factor (*FF*) can be observed, indicating some increase in series resistance. However, all modules show the same trend/slope, endorsing the statement in the introduction to this paper that ECAs can have at least similar reliability and durability to standard lead solder contacts.

Electroluminescence (EL) images confirm the stability of the ECA contacts on such PERC cells, with little visible change within the testing period. In a parallel long-term testing sequence, shingled modules using 1/6-cut cells were also investigated. Generally, the EL images appeared similar to the ones shown later in Fig. 8 but with the addition of other types of visible defects, such as greyish areas that appear in most cells, but underlie a sort of reversible process. A combined microstructure analysis, electrical performance (flash testing) and imaging techniques (EL and magnetic field analysis) is currently under way to more precisely understand the root cause.

Heterojunction cells

Silicon heterojunction solar cells offer the possibility of obtaining energy conversion efficiencies greater than 25% by reducing recombination effects at the metal contacts. This is achieved by displacing the metal contacts from the silicon surface by the deposition of hydrogenated amorphous silicon layers on the surface of the silicon absorber [25]. One challenge of this hydrogenated amorphous silicon layer is its sensitivity to temperatures above 220°C [26]. To overcome this issue, metallization is mostly implemented by low-temperature screen-printed silver pastes which are thermally treated at temperatures around 200°C. In comparison to the standard Ag firing pastes, these low-temperature pastes provide a lower adhesion to the wafer surface [27]. This, and the different microstructure of the metallization, complicates standard interconnection by soldering [28].

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To overcome the challenges of soldering HJT solar cells, the interconnection of ribbons via ECA is one of the main alternatives. In addition to their lead-free nature, the biggest advantages of ECAs for interconnecting HJT solar cells are their low curing temperatures, the fast and easy application via screen printing, the sufficient adhesion (even to busbar-less cells), and the possibility of using structured ribbons. The industrial implementation of this interconnection method has already been achieved, and modules with HJT solar cells interconnected by ECAs can be found on the PV market.

One of the main challenges for ECA interconnections, however, is the high cost of some ECAs, with several of the widely used ones having filler content of up to 80% [29]. Nevertheless, there are different approaches to overcoming this problem, such as drastically reducing the amount of ECA used by variation of the application patterns, as described in more detail below. For example, a continuous ECA line between solar cell and ribbon can be replaced by a dotted line, thereby reducing the ECA amount significantly without losses in module performance [30]. There are also different kinds of ECAs on the market where the silver particle content is reduced, as in the anisotropic conductive adhesives, or is replaced by other metals, such as copper.

With growing demand and further research, the cost of ECAs can be expected to decline over time. In addition, the overall silver consumption in a glued module can be reduced in several ways. One option is the adjustment of the metallization pattern: for example, by using double fingers instead of the full busbars, by going from five busbar configurations to six or more, and combining those approaches with an adjustment of the finger patterns. Another possibility is to use pure copper ribbons instead of silver-coated ribbons [31]. Overall, it can be said that ribbon interconnection with ECAs is an ideal approach for HJT modules, and the problem of higher costs is currently being tackled in R&D by different approaches.

In particular, the reduction of silver consumption in PV is one of the most relevant topics because of environmental impact and economic reasons, with the PV industry being one of the main worldwide silver consumers, representing about 10% of global demand. Anticipating a continuous solar industry expansion, technological breakthroughs are necessary in order to reduce the silver consumption and avoid silver shortage issues.

An initial optimization has to be implemented at the cell design level. Increasing the number of ribbons or wires on the cell layout allows a decrease in the quantity of silver employed in

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cell metallization. However, when using ECA interconnection technology, this solution may imply an increase in the amount of ECA itself and the number of ribbons; hence, an optimal trade-off needs to be found. A second optimization solution is to reduce the silver consumption during the interconnection process at the module level. Indeed, several paths could be considered:

- Reduce the silver content in ECA.
- Reduce ECA consumption.
- Implement ribbons/wires without a silver coating.

All of these solutions should be implemented while maintaining the same module performances and reliability.

Within the framework of the Horizon 2020 GOPV project [32], CEA-INES investigated the reduction of the amount of ECA in HJT cells. The reliability after TCT400 (IEC 61215) of samples with different ECA pad designs, allowing ECA reductions of 40, 45, 55 and 65%, was compared to the reference – a sample with full ECA lines deposited. Results of the tests showed that samples with a significant decrease in ECA consumption of 40–45% could withstand up to twice the TCT norm, with a relative P_{mpp} loss of –2.0% and a ΔFF of –0.5%, vs. initial levels, which are similar to the losses obtained with the reference design.

In a second study, the reduction of the silver content in the ECA composition was evaluated at the module manufacturing level. Nine different ECA pastes were used for that experiment, having silver contents of 60%, >50%, and <50%. Among those with less than 50% silver, two had copper added in their composition in the following ratios: 15:70% Ag to Cu for the first, and 30:60% for the second. The samples were manufactured with one ECA pad configuration that already allowed a 40% ECA reduction, and then the adhesion of the ribbons was measured with a peel force tester. Results showed that the ribbon adhesion was greater than 0.57Nmm^{-1} for most of the samples, and that only one discarded sample had a lower adhesion, around 0.28Nmm^{-1}. After TCT200, one sample with less than 50% silver content exhibited the best performance by far, in compliance with the

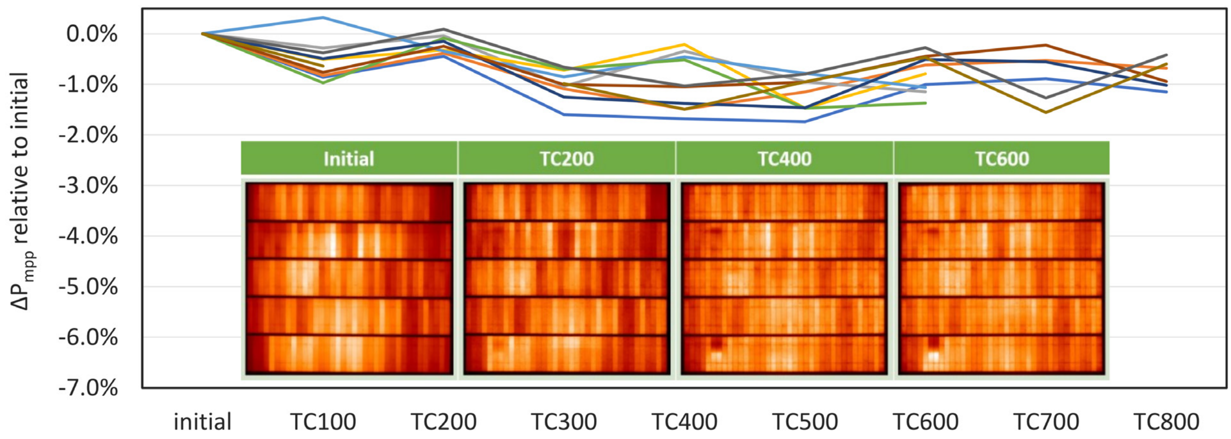

Figure 8. Evolution of P_{mpp} for mini-modules submitted to TCT800 and TCT600. The inset shows the EL images through the accelerated ageing process of a different but related shingled module with five strings bussed in parallel.

IEC norm, with a P_{mpp} loss of around –1.2%.

To conclude, the possible reduction of the quantity of ECA per cell demonstrated by CEA-INES may lead to a significant decrease in silver consumption when the ECAs used have less than 50% silver content. Furthermore, most manufacturers have launched numerous new products in recent years, and an acceleration of further development in ECA technologies is expected with the large-scale industrial implementation of HJT modules. Further improvements in the compatibility of ECA and silver-free wire/ribbon coatings could also lead to a cost reduction factor of a third, enhancing the very promising results already obtained.

HJT reliability

ECA-based interconnections are particularly interesting for high-efficiency architectures, such as HJT solar cells or the latest generations of TOPCon cells, for which low or moderate temperature processes are often required (<200°C for HJT devices, for example). In the case of HJT cells, several tests to study ECA shingling interconnection reliability have recently been conducted at CEA-INES within the framework of the EU's Horizon2020 HighLite project, with consortium partners spanning tool manufacturers, ECA producers and several leading PV research institutes [33].

In one study, strings of HJT shingled cells were embedded into mini-modules and placed into climate chambers for up to 800 thermal cycles, in accordance with the IEC61215-2 norm requirements (–40°C/85°C). As shown in Fig. 8, the P_{mpp} losses after TCT800 were in the range 0.41–1.15% for a first batch of samples. EL images of a different but closely related shingled module are shown in the Fig. 8 inset and provide further qualitative support.

In another test, several quantities of one type of deposited ECA were tested and combined with different solar cell thicknesses (160μm, which is the current standard, and 120μm). Mini-modules were tested up to TCT600, with a maximal degradation in P_{mpp} of 2.6%. The samples that showed the strongest degradation on average (2.6%) were made of 120μm cells with only 1.6mg of ECA per shingle stripe. As expected, those that showed the best reliability (–0.7%) had the larger amount of 6.5mg of ECA per shingle stripe for 160μm-thick cells. Standard quantity deposition of 3.3mg showed equivalent reliability for both thicknesses: close to –1.8% on average after TCT600. Larger strings of 37 shingle stripes were also submitted to thermal cycling tests, and both cell thicknesses showed an average P_{mpp} loss of 2.4% with standard ECA quantity deposition. A PV module made of five large shingle strings bussed in parallel reached a P_{mpp} degradation of less than 2.8% after TCT600.

Although ECA-based shingle interconnection with HJT solar cells is still the subject of R&D efforts, the results obtained to date demonstrate the excellent reliability of the currently developed interconnection technology. Further studies of shingling reliability will be carried out with the aim of improving shingle HJT technology from an economic and environmental point of view, by reducing the quantity of silver used (at the grid metallization and ECA levels) and the solar cell thickness, as well as by increasing the active surface area per module.

Shingling interconnection

ECAs can be used for the direct front-to-rear interconnection of solar cells. This technology is called *shingling*, since the solar cells slightly overlap in a similar way to shingled roof tiles. Shingled solar modules yield an increased power density, as shingling results in an increased overall packing density in the module. Furthermore, the ohmic losses related to the ribbons used to interconnect the solar cells within a conventional solar module are eliminated. These advantages of shingling technology can translate to an absolute gain in module efficiency of up to around 1.9% [34]. Hence, shingled solar modules further reduce the gap between solar cell efficiency and module efficiency.

An important aspect of solar cell interconnections is the thermomechanical stresses exerted on the connection during production and normal operation; for example, it has been shown that solar cells are shifted relative to each other while the laminate is cooling down [35]. In shingling, the ECA bond between the solar cells must ensure both a reliable mechanical and a reliable electrical connection at all times. In particular, ECAs must be able to withstand the shear stresses exerted on shingled joints, as shown in Fig. 9.

“ECAs must be able to withstand the shear stresses exerted on shingled joints.”

The schematics in Fig. 9(a) illustrate the deformation modes of the ECA joint (orange) during temperature changes of the PV laminate. The reference temperature is the temperature of the cross-linking reaction of the encapsulant during lamination (~150°C). After lamination, the glass governs the thermal expansion of the solar module. Since in operation solar modules seldom reach temperatures higher than T_{ref}, the relevant deformation mode is $T < T_{ref}$, when solar cells move towards each other.

Finite element simulations of thermal cycling in accordance with IEC 61215 [37] have shown that the strain at –40°C is close to pure shear strain [36], with mean absolute shear strains of $|\varepsilon_{xy}| \cong 6.5\%$ and mean absolute shear stresses of $|\sigma_{xy}| \cong 25\text{MPa}$. Although these values are strongly dependent on the material data used in the simulations, the implication is that ECAs in shingled solar modules are subjected to stresses and strains of the same order of magnitude as their strength limits.

In addition to the deformation of the joint itself, the solar cells above and below are affected by

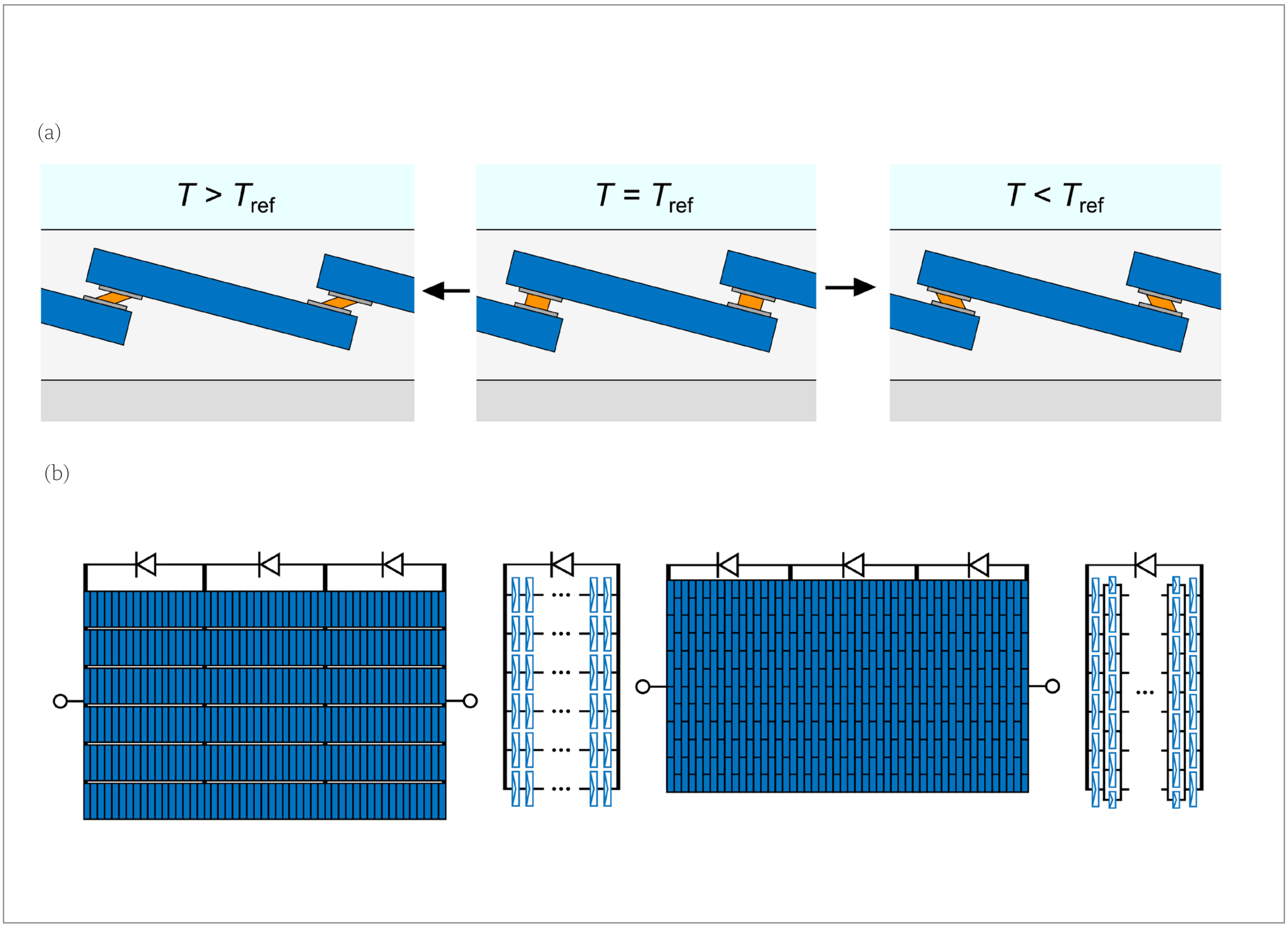

Figure 9. (a) Deformation modes of shingle joints subjected to changes in temperature. For temperatures higher than the stress-free reference temperature T_{ref}, the shingled solar cells move apart, whereas they move towards each other at temperatures less than T_{ref} [36]. (b) Typical interconnection scheme of the shingle string layout and circuit (left), and the shingle matrix layout and circuit (right).

thermomechanical stress. Thermal contraction of the EVA surrounding the joint causes a bending of the solar cells, inducing high tensile stresses on the surface of the solar cell opposing the ECA. These tensile stresses are locally limited to the applied ECA. Characteristic cracking patterns perfectly matching the applied ECA have been found in electroluminescence images after thermal cycling ageing. Because of the asymmetric structure of PV laminates, the highest stresses occur on the solar cell surface facing the backsheet. The defect can occur in monofacial solar cells, but can only be observed in bifacial cells in combination with transparent backsheets, since detection requires electroluminescence techniques. Therefore, it might go unnoticed in conventional laminates with opaque backsheets. So far, it has not been possible to link this cracking mechanism to significant losses in power; however, the mechanism was presented at the 11th SiliconPV 2021 [38].

Besides the thermomechanics of ECA-bonded joints and the as-yet unresolved issue of recombination at the cut cell edges [39], shingled solar cell interconnection opens up possibilities for more sophisticated solar module layouts, such as the shingle matrix interconnection (see Fig. 9(b), right) [40]. Such solar modules are much more resilient with regard to partial shading [41]; consequently, shingled solar modules and especially shingle matrix modules are well suited to vehicle and building integration. M10 Industries now offers a high-throughput shingling stringer, which was developed in conjunction with Fraunhofer ISE within the public German Shirkan project [42], and which is capable of implementing both the linear- and matrix-shingled module concepts.

When shingled modules are produced in a high-volume manufacturing environment, the shingling of strings is achieved using dedicated equipment which is considerably different from that used for the mainstream stringing and tabbing approach. In fact, cells first have to be separated into shingle stripes (for example, by traditional laser scribe and cleave, or using newer techniques such as thermal laser separation); the ECA then has to be deposited (screen/stencil printing or dispensing) before the shingle stripes are arranged in the typical overlapping scheme. Current-generation tools – such as Applied Materials' Sonetto 2.0 – can assemble up to 4,000 full cells per hour in a dual-lane configuration. In practice, five or six shingles are processed simultaneously within a cycle time of 1.8s, equating to 20,000–24,000 shingle stripes per hour, and next-generation tools have already been announced that are capable of 6,000 M12-sized full cells per hour [43].

When depositing ECAs by screen printing, several variables need to be considered in production:

- *Rheology variations:* ECAs should be as stable as possible in terms of rheology variations (thixotropy) over time in order to maintain constant deposits.
- *Temperature and humidity:* environmental changes, such as a temperature increase, may induce partial curing of the ECAs. The risk is higher if the ECA is deposited on the cell and more of the surface is exposed.
- *ECA lifetime on screen:* different chemistries react differently to the rolling mechanism introduced by the printing process.
- *Printing parameters:* accurate controls of print force, speed, distance to the substrate, and stroke are essential to achieving a consistent product.

By stabilizing and controlling all of the above elements, it is possible to achieve suitable production yields, which normally surpass 98.5% (from cells-in to strings-out, including reworking). Because of its unique approach, shingling-based interconnection can be implemented with only relatively minor equipment modifications for large wafers, thin wafers, low-temperature cells, lead-free modules and building-integrated PV (BIPV) applications.

An alternative approach investigated within the ongoing German Hossa research project by a consortium of tool suppliers, module manufacturers and research institutes [44] relies on a modified process order for high-throughput industrial shingling. In this approach, the ECA is applied first to the uncut shingled cells, then the laser scribing is performed adjacent to the deposited ECA, as shown in Fig. 10; in a final step, the stringer separates the cells and assembles the strings. In this way, the difficult processing of many small cell stripes is postponed to a later process step, with significant benefits to process and machine simplification. In order to implement this approach, the ECA has to be optimized with particular regard to the pot life or on-part life, while the laser process needs to be adjusted such that the final properties of the ECA bond remain unaffected. Results have shown that, despite laser-induced changes to the surface and shape of the ECA line (as shown in Fig. 10), this can be achieved when using the correct laser and process parameters, even when lasering very close to the ECA.

Anecdotally, the long-term reliability of shingled modules is exceptional, with several manufacturers offering warranty extensions of at least five years vs. their non-shingled counterparts. Notwithstanding the efforts described below to determine the failure modes and root causes of degradation in shingled modules and other formats that employ ECA for bonding, despite somewhat contradictory results in the published literature, the reasons for such high levels of manufacturer confidence can be readily seen by considering again the data in Figs. 3, 7 and 8. Of note is the fact that several BOM combinations

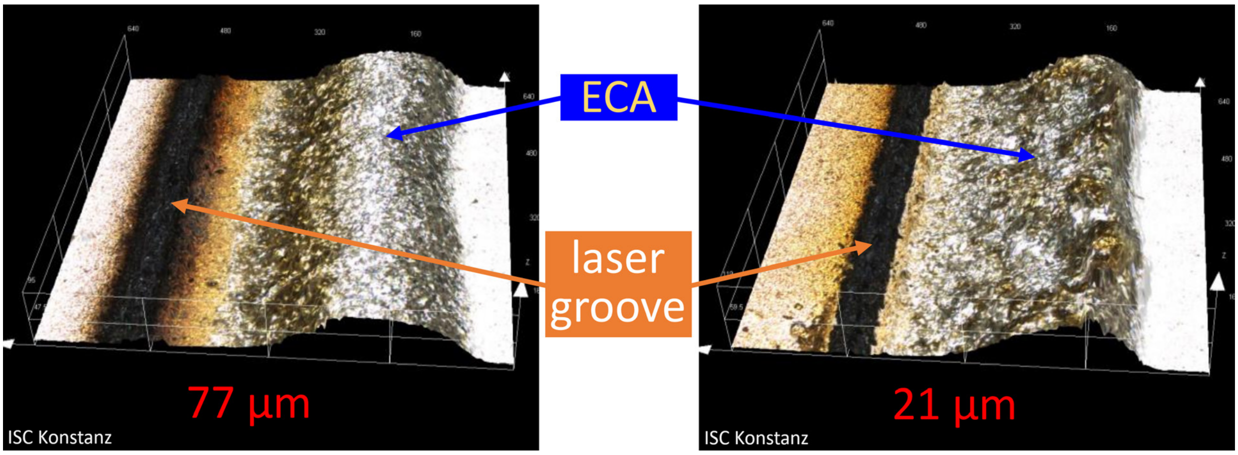

Figure 10. Laser scanning microscope images of laser-etched grooves adjacent to uncured ECA lines, where the separation between laser groove and ECA is 77µm (left) and 21µm (right).

can withstand thermal cycling for periods well in excess of the IEC 61215 pass criterion for TCT (degradation less than 5% with up to 200 cycles); indeed, several combinations showed the potential for only around 1% degradation with up to 700–1,400 cycles. The same combination that exhibited less than 1% degradation in Fig. 3 also exhibited less than 1.5% degradation for up to 4,250h of damp heat testing (data not shown).

Further ECA reliability studies

Currently, the reliability of modules built using ECAs is of great interest in the scientific community, but not many studies have been published and relevant work is ongoing. Additionally, qualification tests for ECAs in PV modules have not yet been developed and implemented [45,46]. Mesquita et al. [47] proved scanning acoustic microscopy (SAM) to be a powerful tool for non-destructively characterizing modules built using ECAs. In their work, the authors could clearly distinguish between defective and non-defective adhesive after accelerated ageing tests. Schiller et al. [48] proposed an accelerated TCT able to give, in a shorter time, results that are similar to the typical IEC TCT. The proposed test might be useful during material development to reduce testing time.

Three ECA formulations have been tested by Bauermann et al. [49], two of which fulfilled the IEC 61215 criteria in terms of power loss after HFT, DHT and TCT. None of the formulations, however, performed comparably to traditional soldered ribbon, possibly because of the negative interaction between adhesive and water. Additionally, the adhesives showed differences depending on the stress applied, thus indicating that a climate-specific application should be considered. Klasen et al. [50] proposed a model able to predict, in comparative studies, mechanical stresses in the joints of shingled solar cells using different geometries.

With regard to the mechanical behaviour and the fracture toughness of the cured resin in high-efficiency cell concepts and reduced cell thicknesses, the consideration of mechanical strain is especially important. Springer et al. [51] recently investigated the viscoelastic properties of different ECA formulations. Chemical composition and cure conditions had a big influence on viscoelastic material properties. Furthermore, the response to dry and damp heat exposure was investigated. Depending on the ECA type, the observations ranged from no change to significant changes in the viscoelastic properties. Damp heat exposure caused embrittlement to a point, where even small strains imposed during dynamic mechanical analysis caused fracture. Moreover, changes in thermal expansion behaviour were detected after ageing. Embrittlement of ECAs has also been reported elsewhere [52].

So far, only a limited number of papers [53–55] dealing with the fatigue behaviour of different types of cell interconnection have been published, and they give contradictory results. Pander et al. [55] found that the use of ECAs in silicon solar cells led to a reduction in strain within the silicon compared to soldering. They also studied fatigue of solar cell interconnectors, and designed the loading profile during the fatigue test so as to achieve the same strain amplitude in the cell gaps as that found in a full-size module simulation under ±1,000Pa, which corresponds to the IEC testing standard [53].

"Modern ECAs are consistently proving themselves to be one of the key technologies in the future of PV."

Dietrich et al. [53] also investigated fatigue of solar cell interconnectors, but chose the test amplitude in such a way that the failure occurred in less than 10,000 cycles; however, the authors did not give details of the load levels applied in their fatigue test. Zarmai et al. [56] studied thermomechanical damage and fatigue life of solar cell solder interconnections, and reported calculated values of 21MPa for the maximum stress concentration in the solder joint. This value was obtained through thermal cycling tests in accordance with IEC 61215 [57].

Oreski et al. [58] investigated the cyclic fatigue behaviour of two different ECA types, and found a significant difference in the resistance to fatigue. One explanation lies in the intrinsic fatigue resistance of the materials, but also the sample preparation may have an impact on the fatigue resistance. Regarding the cyclic fatigue behaviour of the ECA types studied, the S–N curves depicting cyclic stress as a function of cycles to failure are either significantly above the mean stress levels reported for interconnections in PV modules [53,54] or in a similar range to them [56]. The reported values for the number of cycles to failure for soldered bonds are also in a similar range.

For ECA-bonded test modules, a slight power loss after thermal cycling, damp heat and irradiance exposure has been observed [58]. In that study, the power loss was attributed not only to failure of the ECA bond but also to additional factors such as sample preparation and cell damage that was present from the start. In the same study, the compatibility of different ECA formulations and various encapsulation films and ribbon materials was investigated. No harmful interactions were found between the ECA formulations examined and the different encapsulant films after lamination and ageing tests. The main outgassing products were identified as fragments of the hardener. In addition, no migration of silver particles was observed. ECAs were compatible with all tested ribbon types (Cu, Ag, SnAgCu), since no delamination or discoloration after lamination or accelerated ageing tests was observed.

Summary and outlook

Whether in shingling, in low-temperature interconnections or as solder replacement, modern ECAs are consistently proving themselves, through their material performance, process flexibility and reliability in application, to be one of the key technologies in the future of PV. Considering the maturity and inherent material and process limitations of traditional lead and lead-free metal soldering technology compared to the vast range in potential of the filler–adhesive platform offered by ECAs, the trajectory of development is clearly leaning towards ECAs becoming a dominant interconnection medium. Of course, with the currently high rate of progress and innovation in PV, coupled with the ponderous momentum of an industry in which multi-GW factories can take years to plan and build, and not forgetting the financial and economic realities of decision-making in a highly competitive global market, only time will tell if this turns out to be the case.

It is accepted, however, that an exponential increase in PV production output will be required over the next decade to meet national renewable energy targets and international emissions reduction agreements (such as the Paris Climate Accords). That being the case, as well as the natural evolution of PV market share towards higher-efficiency cell concepts, not to mention the inevitable progression towards tandem cells that use silicon and temperature-sensitive thin-film technologies (such as perovskites and GaAs, which are now firmly on the horizon), the future is certainly looking very bright for ECAs.

References

[1] Nicolics, J. & Mündlein, M. 2007, "Electrically conductive adhesives", in *Micro- and Opto-Electronic Materials and Structures: Physics, Mechanics, Design, Reliability, Packaging,* Suhir, E., Lee, Y.C. & Wong, C.P., Eds. New York, USA: Springer, pp. B571–B610.

[2] Battermann, A. 2012, "Joining technology that's fit for the future", *Adhes. Adhes . Sealants,* Vol. 9, pp. 40–43.

[3] Morris, J.E. & Wang, L. 2014, "Isotropic conductive adhesive interconnect technology in electronics packaging applications", in *Adhesion in Microelectronics,* Mittal, K.L. & Ahsan, T., Eds. Hoboken, NJ, USA: John Wiley & Sons, Inc, pp. 173–210.

[4] Li, Y., Moon, K.-S. & Wong, C.P. 2005, "Electronics without lead", *Science*, Vol. 308, No. 5727, pp. 1419–1420.

[5] Yim, M.J. & Paik, K.W. 2006, "Recent advances on anisotropic conductive adhesives (ACAs) for flat panel displays and semiconductor packaging applications", *Int. J. Adhes. Adhes.,* Vol. 26, No. 5, pp. 304–313.

[6] Beier, B. et al. 2001, "Electrical conductive adhesives", *Proc. 17th EU PVSEC,* Munich, Germany, pp. 812–815.

[7] Frisson, L. et al. 2001, "Conductive adhesives as an interconnection technique for very thin solar cells", *Proc. 17th EU PVSEC,* Munich, Germany, pp. 414–416.

[8] Lalaguna, B. et al. 2008, "Evaluation of stress on cells during different interconnection processes", *Proc. 23rd EU PVSEC,* Valencia, Spain, pp. 2705–2708.

[9] Bultman, J.H. et al. 2003, "Fast and easy single step module assembly for back-contacted c-Si solar cells with conductive adhesives", *Proc. 3rd WCPEC,* Osaka, Japan, pp. 979–982.

[10] Scherff, M.L.D. et al. 2006, "10 × 10 cm² HIT solar cells contacted with lead-free electrical conductive adhesives to solar cell interconnectors", *Proc. 4th WCPEC,* Waikoloa, Hawaii, USA, pp. 1384–1387.
[11] Schwertheim, S. et al. 2008, "Lead-free electrical conductive adhesives for solar cell interconnectors", *Proc. 33rd IEEE PVSC,* San Diego, California, USA, pp. 1–6.
[12] Späth, M. et al. 2011, "Hetero-junction module technology", *Proc. 26th EU PVSEC,* Hamburg, Germany, pp. 3121–3124.
[13] teamtechnik 2018, "Lower costs, more efficiency: Russian module manufacturer and PV project developer Hevel LLC switches to adhesive technology from teamtechnik for its HJT modules", Press Release, 25 Sep. [https://www.teamtechnik.com/en/news/].
[14] teamtechnik 2018, "Major contract for teamtechnik: Italian PV manufacturer orders stringers for production of high efficiency modules with HJT cells", Press Release, 12 Feb. [https://www.teamtechnik.com/en/news/].
[15] Chunduri, S.K. 2011, "Sticky and cool", *Photon International,* Vol. 2011, No. 11, pp. 158–165.
[16] Yan, F. et al. 2013, "Evaluation of CIGS cell interconnection methods", *Proc. 39th IEEE PVSC*, Tampa, Florida, USA, pp. 2064–2067.
[17] SunPower 2021, "Performance Solar Panels" [https://sunpower.maxeon.com/uk/solar-panel-products/sunpower-performance-solar-panels].
[18] Devoto, M.I. et al. 2021, "Contact resistivity of ECA bonded joints", *AIP Conf. Proc.,* Vol. 2367, No. 1, p. 020011.
[19] Geipel, T. 2018, "Electrically conductive adhesives for photovoltaic modules", Technical Report, Fraunhofer ISE.
[20] Devoto, M.I. et al. 2021, "Measuring the contact resistivity of ECA-based joints", *Proc. 38th EU PVSEC*, Lisbon, Portugal.
[21] Bennett, I.J. et al. 2014, "An overview of developments in foil-based back-contact modules", *Proc. 29th EU PVSEC,* Amsterdam, The Netherlands.
[22] Timofte, T. et al. 2021, "Reliability assessment for industrial soldered and glued BJ-BC solar cell interconnections", *Proc. 38th EU PVSEC,* Lisbon, Portugal.
[23] Sweatman, K.W. et al. 2016, "Controlling voiding mechanisms in the reflow soldering process", *Proc. IPC APEX Expo 2016,* Las Vegas, Nevada, USA.
[24] Habenicht, G. 2009, *Kleben*, Springer.
[25] Haschke, J. et al. 2018, "Silicon heterojunction solar cells", *Sol. Energy Mater. Sol. Cells,* Vol. 187, pp. 140–153.
[26] De Wolf, S. & Kondo, M. 2009, "Nature of doped a-Si:H/c-Si interface recombination", *J. Appl. Phys.,* Vol. 105, No. 10, p. 103707.
[27] Gierth, P. et al. 2013, "Comparison of NiV and polymer paste metallization as low temperature interconnection of high efficiency heterojunction solar cells", *Proc. 28th EU PVSEC,* Paris, France, pp. 464–467.
[28] De Rose, A. et al. 2017, "Low-temperature soldering for the interconnection of silicon heterojunction solar cells", *Proc. 33rd EU PVSEC,* Amsterdam, The Netherlands, pp. 710–714.
[29] Lewis, H.J. & Coughlan, F.M. 2008, "An overview of the use of electrically conductive adhesives (ECAs) as a solder replacement", *J. Adhes. Sci. Technol.,* Vol. 22, No. 8–9, pp. 801–813.
[30] Kaiser, C. et al. 2020, "Reduction of ECA amount for the ribbon interconnection of heterojunction solar cells", *Proc. 37th EU PVSEC* (virtual event), pp. 1086–1090.
[31] Geipel, T. et al. 2019, "Industrialization of the ribbon interconnection of silicon heterojunction solar cells with electrically conductive adhesives", *Proc. 36th EU PVSEC,* Marseille, France, pp. 916–925.
[32] GOPV. EU Horizon2020, Grant Agreement Number 792059.
[33] HighLite. EU Horizon2020, Grant Agreement Number 857793.
[34] Mittag, M. et al. 2017, "Cell-to-Module (CTM) analysis for photovoltaic modules with shingled solar cells", *Proc. 44th IEEE PVSC,* Washington DC, USA.
[35] Eitner, U. 2011, "Thermomechanics of photovoltaic modules", Dr.-Ing. dissertation, Martin-Luther-Universität Halle-Wittenberg, Halle-Wittenberg.
[36] Klasen, N. et al. 2019, "FEM simulation of deformations in strings of shingled solar cells subjected to mechanical reliability testing", *AIP Conf. Proc.,* Vol. 2156, No. 1, pp. 020016-1–020016-11.
[37] IEC 61215-2:2016, "Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 2: Test procedures".
[38] Klasen, N. et al. 2021 [submitted], "Root cause analysis of solar cell cracks at shingle joints", *Sol. Energy Mater. Sol. Cells.*
[39] Tune, D. et al. 2020, "Measuring and mitigating edge recombination in modules employing cut cells", *Proc. 37th EU PVSEC* (virtual event).
[40] Klasen, N. et al. 2021 [forthcoming], "Performance of shingled solar modules under partial shading", *Prog. Photovolt: Res. Appl.*
[41] Klasen, N. et al. 2021 [forthcoming], "'Shading Resilience' as a general measure of shading tolerability in PV modules", *IEEE J. Photovolt.*
[42] Shirkan project. BMWi, Funding Ref. No. 03EE1026A.
[43] Taiyang News 2021 [http://taiyangnews.info/technology/day-2-taiyangnews-whats-hot-in-european-solar-rd/].
[44] Hossa project. BMWi, Funding Ref. No. 03EE1014D.
[45] Hu, Y. & French, R.H. 2019, "Degradation and failure mechanisms of PV module interconnects" in *Durability and Reliability of Polymers and Other Materials in Photovoltaic Modules,* Yang, H.E., French, R.H & Bruckman, L.S., Eds. Amsterdam: Elsevier, pp. 119–134.
[46] Oreski, G. et al. 2021, "Designing new materials

for photovoltaics: Opportunities for lowering cost and increasing performance through advanced material innovations", Report IEA-PVPS T13-13:2021, International Energy Agency.

[47] Mesquita, L.V. et al. 2019, "Analysis of shingle interconnections in solar modules by scanning acoustic microscopy", *AIP Conf. Proc.,* Vol. 2147, 090003.

[48] Schiller, C.H. et al. 2019, "Accelerated TC test in comparison with standard TC test for PV modules with ribbon, wire and shingle interconnection", *Proc. 36th EU PVSEC,* Marseille, France, pp. 995–999.

[49] Bauermann, L.P. et al. 2017, "Qualification of conductive adhesives for photovoltaic application – Accelerated ageing tests", *Energy Procedia,* Vol. 124, pp. 554–559.

[50] Klasen, N. et al. 2019, "FEM simulation of deformations in strings of shingled solar cells subjected to mechanical reliability testing", *AIP Conf. Proc.,* Vol. 2156, 020016.

[51] Springer, M. & Bosco, N. 2020, "Linear viscoelastic characterization of electrically conductive adhesives used as interconnect in photovoltaic modules", *Prog. Photovolt: Res. Appl.,* Vol. 28, No. 7, pp. 659–681.

[52] Eitner, U. et al. 2012, "Characterization of electrically conductive adhesives", *Energy Procedia,* Vol. 27, pp. 676–679.

[53] Meier, R. et al. 2016, "Microstructural optimization approach of solar cell interconnectors fatigue behavior for enhanced module lifetime in extreme climates", *Energy Procedia,* Vol. 92, pp. 560–568.

[54] Pander, M. et al. 2013, "Lifetime estimation for solar cell interconnectors", *Proc. 28th EU PVSEC,* Paris, France, pp. 2851–2857.

[55] Pander, M., Schulze, S.-H. & Ebert, M. 2014, "Mechanical modeling of electrically conductive adhesives for photovoltaic applications", *Proc. 29th EU PVSEC,* Amsterdam, The Netherlands, pp. 3399–3405.

[56] Zarmai, M.T. et al. 2017, "Evaluation of thermo-mechanical damage and fatigue life of solar cell solder interconnections", *Robot. Comput. Integr. Manuf.,* Vol. 47, pp. 37–43.

[57] IEC 61215-1:2016, "Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 1: Test requirements".

[58] Oreski, G. et al. 2019, "Reliability of electrically conductive adhesives", *Photovoltaics International,* Vol. 42, pp. 38–45

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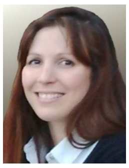

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