

Latest advances of ECA-based tabbing and stringing at CEA-INES

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Abstract

Low-temperature interconnection processes for high-efficiency PV cells will be a key R&D topic in the coming years. In reality, to avoid significant deterioration of the surface passivation, the metallization and interconnection processes of silicon heterojunction (SHJ) cells are limited to temperatures below 200°C; tandem cells with a perovskite subcell demand an even greater reduction in process temperature, namely below 130°C. Moreover, to ensure the sustainability of PV production on a TW scale, the use of scarce materials, especially silver, needs to be reduced, as 10% of the world's supply was already dedicated to PV in 2020. This paper addresses the results obtained in terms of reducing the silver consumption in interconnection technology based on electrical conductive adhesive (ECA) and Pb-free ribbons. The first demonstration of stencil-printing-based ECA deposition with an improved accuracy using equipment from Mondragon Assembly is reported. This equipment allows a minimal amount of ECA deposition while maintaining highly reproducible results, as demonstrated through the fabrication of 400 glass–glass modules and the validation of process reliability. This paves the way towards creating Si/perovskite tandems that involve ECA curing at temperatures below 130°C with sufficient adhesion (> 0.8N/mm) of the ribbon to the cell, as well as offering a means to consistently reduce Ag usage. Furthermore, improvements to the Mondragon Assembly stringer to handle next-generation cells are outlined.

Introduction

The sustainable manufacturing imperative of the PV industry triggered by the exponential growth to a TW-scale annual production capacity in the context of energy transition and sovereignty is redefining technical roadmaps, industrial landscapes and market projections.

The recent European PV renaissance is heavily based on silicon heterojunction (SHJ) technology, with ENEL Green Power and its expansion announcement [1] and Meyer Burger as the major players, and more competitors in the starting blocks [2]. The advantages of SHJ as a passivated contact technology are numerous, such as high power conversion efficiency coupled with a low temperature coefficient and elevated bifaciality, enabling the highest energy yield among single-junction devices [3]. Moreover, the low-temperature process technology and compatibility with thin wafers also make SHJ a low environmental footprint technology [4]. Global SHJ production capacity is

rising in line with the rapid proliferation of n-type wafers and is conservatively projected by ITRPV to take 40–50% of the market share by 2030.

To avoid severe deterioration of surface passivation, the SHJ cell metallization and interconnection processes are limited to temperatures below 200°C. Therefore, SHJ modules integrate low-temperature interconnection technologies with either In- or Bi-based soldering of ribbons or wires like the proprietary SmartWire Connection Technology (SWCT) foils or ribbon tabbing with electrically conductive adhesives (ECAs). This latter technology has matured rapidly, with equipment being offered by several tool manufacturers and technology qualification by leading institutes, complemented by the latest generation of materials from an increasing number of suppliers. Although, historically, the PV industry has relied on soldering because of its reliability, the latest improvements in ECA formulation are reversing this trend, with carefully designed formulations offering superior performance and long-term reliability, as well as compliance with Pb-free regulations that are also emerging in the PV sector [5].

The sustainability of PV production on a TW scale requires a close examination of the availability of scarce materials, with the main concern being the use of Ag, since already 10% of the global supply was directed to PV in 2020 [6]. The current combined silver consumption for cell metallization and module interconnection of bifacial SHJ modules is 35mg/Wp. To reach sustainable levels, Verlinden [7] suggests the ambitious target of less than 5mg/Wp be met by 2030, requiring the co-design of cell and module metallization, the refinement of printing techniques and the (re) introduction of abundantly available copper. An additional strategic aid to meeting this goal is the increase in module performance offered by silicon-perovskite tandem devices as well as their potential to reduce Ag consumption owing to lower current density. The pressure to reduce the use of In and Bi in PV production on a TW scale is even greater, given their limited supply, discouraging the use of low-temperature solder alloys with their current formulation.

This paper presents an overview of ECA-based ribbon tabbing interconnection technology as a workhorse for current SHJ modules, as well

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as the latest advances and roadmaps in terms of performance, reliability, sustainability and compatibility with perovskite-based two-terminal tandems.

ECAs – material properties and CEA-INES's approach to qualifying process development

ECAs are composite materials consisting of electrically conductive particles, primarily silver, in a polymer matrix, such as epoxy, acrylic or silicone [8]. They were first utilized in shingling applications, but have recently also been used in ribbon attachment [9] and became the main alternative to the soldering process for interconnecting solar cells. ECA-based interconnections have various advantages inherited from the family of adhesives, such as a low toxicity (no lead), a tolerance towards mechanical deformation, and a low processing temperature (between 120°C and 200°C compared with 250°C for typical lead-free solder). The low processing temperature is critical to reducing the thermomechanical stress placed on the wafer, and makes the ECA type of interconnection suitable for thin wafers and/or future silicon-perovskite tandem cells.

The conductive fillers confer excellent electrical properties to ECAs, typically a conductivity of around 1–5Ω·cm. However, to achieve such conductivity, the selection of the conductive material is key. Silver is unique in this regard because of the high conductivity of its oxide, even after exposure to heat and moisture. To address the issue of excessive consumption of silver in PV module manufacturing, silver alternatives are under development, for example a silver/copper combination or a new type of conductive particle [10].

The polymeric matrix accords excellent flexibility, giving an advantage of ECA over soldering, in that it can more easily absorb stress induced by thermomechanical processes and by differences in the thermal expansion coefficient of the various materials in the module [11].

To evaluate the PV performance of ECAs, a sequential qualification process has been developed at CEA-INES. First, the process window of the ECA is assessed using differential scanning calorimetry (DSC). DSC is a thermal analysis technique in which the heat flow into or out of a sample is measured as a function of temperature or time, while the sample is exposed to a controlled temperature programme. It is a very powerful technique for evaluating material properties, such as glass transition temperature, melting, crystallization, specific heat capacity, cure process, purity, oxidation behaviour and thermal stability. DSC also measures the rate of heat flow and compares differences between the heat flow rate of the test sample and known reference materials. This difference determines the variations in material composition, crystallinity and oxidation.

Based on the input outlined above, a process optimization for the interconnection is begun in

“The low processing temperature makes the ECA type of interconnection suitable for thin wafers and/or future silicon/perovskite tandem cells.”

order to determine the screen- or stencil-printing parameters for the ECA deposition and curing condition with direct heat or IR heating. The fast-feedback method of adhesion measurement of the ribbons on the cells assists the process optimization, aiming for a minimum value of between 0.5 and 1N/mm in a 180° peel-test configuration. Once the process conditions have been defined, strings of full or half-cut SHJ (or PERC) cells are fabricated in an automated manner, and mini-modules are manufactured with a previously qualified bill of materials (BOM) for initial performance and (highly) accelerated ageing in a thermal cycling chamber [12]. The electrical parameters are measured after 100, 200 and 400 cycles, with a particular focus on the fill factor (*FF*) of the module and the use of electroluminescence imaging to reveal possible series resistance increases and interconnection failures.

Further material analyses are performed to gain a deeper understanding of the mechanical behaviour. In particular, measurements taken on the cured ECA sample using dynamic mechanical analysis (DMA) give access to the thermomechanical properties (*E'*, *E''*, time–temperature superposition); these can then be implemented in a computational simulation of the thermomechanical behaviour of the module (during lamination and thermal cycling), or later on in real application conditions. Silver content measurement complements the characterization for purposes of comparison of the different ECAs, in particular in a life cycle analysis, which is also integrated in CEA-INES's qualification protocol.

In the final stage of qualification, industrial-size modules with 144 half-cut cells and qualified BOM are fabricated with selected ECAs and submitted to a sequence of thermal cycling and mechanical stress testing in static or dynamic mechanical loading in accordance with IEC 61215, where electrical parameters are controlled at intermediate intervals. In the case of an interconnection/module failure, opto-electrical measurements are supplemented with an in-depth analysis using advanced material characterization tools (SEM-EDX, TEM, etc.), and thus providing suggestions for improvements.

The first round of lowering Ag consumption – ECA reduction through process and deposition optimization

The amount of silver consumed along the cell-interconnection processes is linked to the number of ribbons and the amount of ECA deposited on each cell busbar (BB). To achieve economic sustainability, it is imperative to find a method to decrease silver consumption. The first solution is to reduce the amount of ECA deposited on each BB. At the beginning of this optimization study, a straight solid

line of ECA, 600µm wide, was deposited on each BB; for a half-size M2 cell, using a reference ECA, this represents about 5mg of ECA per BB. Considering the upcoming increases in wafer size and the use of multiple ribbons, a drastic reduction is necessary in order to cut down on Ag consumption and to keep manufacturing costs competitive. To achieve this result, the four main possibilities are:

1. Reduce the ECA line width.
2. Reduce the deposited ECA thickness.
3. Deposit ECA pads instead of a continuous ECA line.
4. Use ribbons without an Ag coating.

Ideally, a combination of all four of the above mitigating approaches would be the most appropriate and promising route to take.

The reduction of the ECA line width is strictly related to the stringer machine accuracy. Indeed, using a 0.6mm-wide ribbon and an ECA line width of 400µm, a relative positioning accuracy of 100µm per cell is required for both ECA deposition and ribbon/wire positioning. Moreover, decreasing the ECA line width will directly reduce the adhesion and the contact surface with the ribbons. The tuning of the ECA deposition thickness can also even be detrimental, interfering with the cell metallization and the mechanical stability of the ribbon. Consequently, the ECA thickness has to remain greater than that of the cell metallization for example.

A preliminary study (the CEA reference) was carried out on a semiautomatic screen-printing and stringer unit to cure the ECA. Ribbons were manually placed on the cells, which limited the risk of

misalignment. Analyses of the ECA mass deposition amount and the adhesion strength of the ribbons on the cell, as well as a thermal cycling reliability test, were performed. The initial screening test revealed some already interesting results:

- Importantly, a too aggressive reduction of the ECA line thickness (ECA thickness should remain greater than that of the metallization, typically between 10 and 15µm) is not compatible with an industrial process because of the low ribbon/cell adhesion (<0.2N/mm). The handling of such strings would lead to a very high scrap rate in an automatic production line.
- With the Mondragon Assembly stringer (accuracy of 100µm), a line reduction down to 200µm with 0.6mm ribbons could be possible.
- The implementation of pads allows the highest amount of ECA reduction (40–65% ECA mass reduction). However, a minimum amount of ECA has to be deposited in order to guarantee reliability.

These preliminary results led to the following test plan, carried out using the ECA tabber–stringer from Mondragon Assembly. Width reduction and the use of pads were implemented, as well as a combination of both approaches.

A significant overall reduction in ECA was obtained (up to 65%). However, thermal cycling test results at 400 TC showed a slight decrease in reliability with the higher ECA reduction designs (Fig. 1), revealing an optimum trade-off for the ECA reduction with the reference paste combination ('Pads B', 'Width 1' in Fig. 1(a)). A loss of less than 1% was observed after 400 TC with a 45% (11mg/W) reduction in deposited weight.

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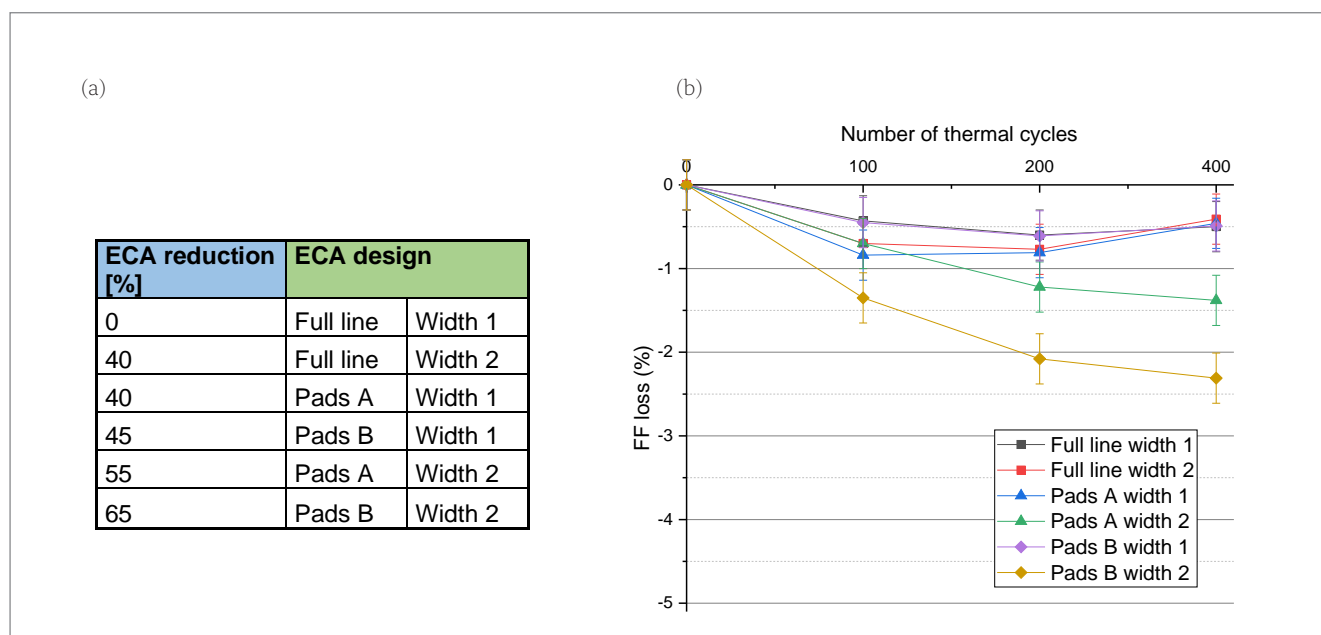


Figure 1. (a) Description of the different ECA designs, along with the silver reductions achieved. (b) Fill factor (FF) loss after 100, 200 and 400 thermal cycles (–40°C to +85°C).

Reduction of ECA deposited weight with stencil printing and the advantages over screen printing

Stencils have been widely used for the last 30 years in the surface mount technology (SMT)/printed circuit board (PCB) industry for printing solder paste onto boards. An SMT board, however, differs significantly from a thin, fragile silicon solar cell, and the nature of the solder pastes is entirely different from that of ECA adhesives, not to mention the speed of printing. Still, lessons can be learnt from the SMT stencil-printing application, but clearly their practice cannot be copied.

In the pursuit of printing finer lines with a higher aspect ratio, the effective open area in the screen mesh becomes smaller and the quality of the opening in the emulsion layer poorer. The open area and the interior finish are important aspects for ECA transfer into the screen mask area and for the release of the ECA onto the substrate [13]. A finer mesh, better emulsion material, and improved screen manufacturing will help, but ultimately these parameters will be limited in screen printing. In stencil printing, the open area is larger: for a typical front-side screen with 280 mesh, the open area is 53%, while for a laser-cut stainless steel stencil, the open area is 100% in this case (Fig. 2).

Stencil-printing technology uses a metal plate with openings as a mask. The process mode is 'back and forth', meaning that the ECA is scraped one way by the first metal blade and then the other way by a second metal blade. The thickness of the stencil mask determines the thickness of the deposited adhesive. In contrast, screen-printing technology uses a meshed screen and the printing is done in only one direction: a squeegee scrapes the ECA through the openings, and then a metal counter-squeegee spreads it over the entire surface of the mask, ready to be scraped again.

Fig. 3 compares the conductive adhesive deposits obtained with the stencil and with the screen. It can be seen that the sharpness of the print is better with stencil technology; this is due to the absence of any gap between the stencil mask and the cell, and because the hole of the stencil is completely open, which allows better release of the ECA. It was also observed that on the stencil screen, in contrast to the mesh screen, there is no displacement of ECA by capillary action under the screen, which makes it possible to have a sharp edge and a width of deposit equal to the width of the opening of the screen.

Mondragon Assembly recently developed an industrial ECA tabber-stringer, the 'ECA-MTS', for the ECA interconnection of high-efficiency cells, after productive work within the European-funded GOPV project. The improved accuracy of the ECA-MTS leads to a very small quantity of deposited ECA to perform a reliable interconnection. This will have a direct effect on Ag consumption for a module, while permitting the use of a narrower ribbon or smaller wire, which results in a reduction in the shadowing effect. In addition, a more accurate positioning of

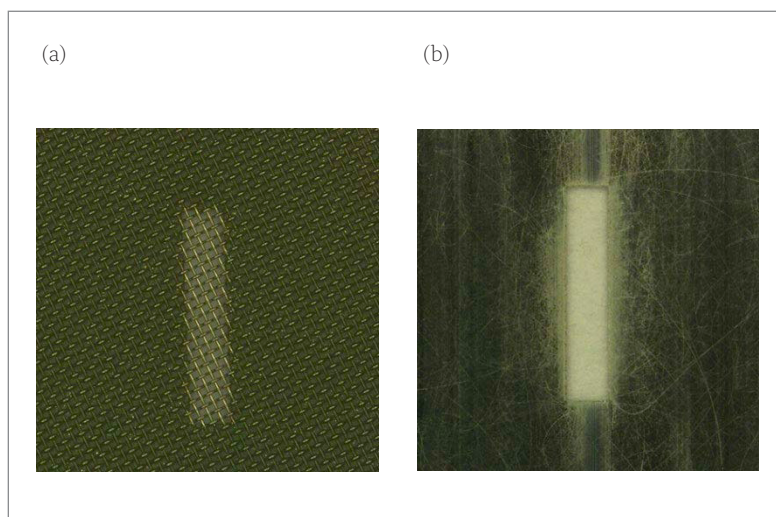


Figure 2. (a) Screen opening. (b) Stencil opening.

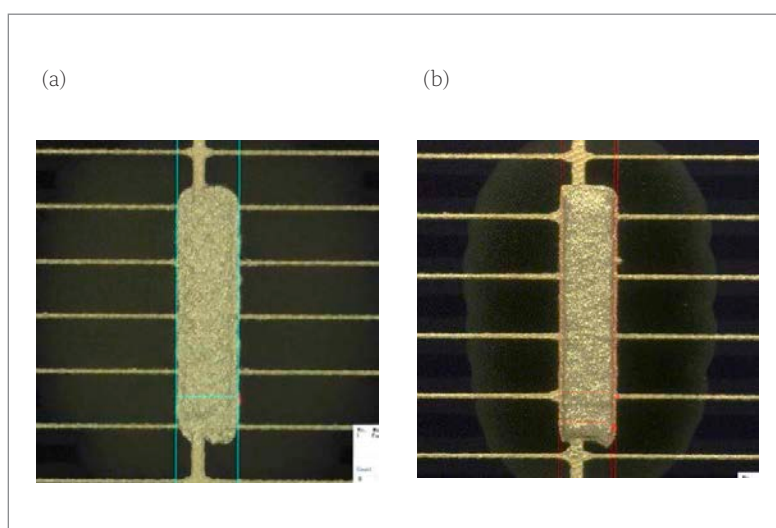


Figure 3. Print quality comparison: (a) with a screen, and (b) with a stencil.

the ribbon will also affect the metallization design – another way to limit Ag consumption at the cell level. The new equipment will therefore significantly affect the levelized cost of electricity (LCOE) in relation to module manufacturing, thus allowing the ECA interconnection process to compete with the soldering process for heterojunction technology (HJT) cells.

The ECA-MTS industrial machine will be an evolution of an initial pilot line developed within the framework of the GOPV project, where the stencil-printing method was selected for ECA deposition because of diverse beneficial factors, such as longer durability, higher dimensional reliability, lower mechanical loads to the cell, and reduced downtime of the tool. The aforementioned advantages have been widely explained throughout this paper.

One of the highlights of this new equipment is the high accuracy when depositing the ECA and positioning the wires on the cell. The deposition accuracy is achieved by the long-term dimensional stability of the stencil pattern, and by the auto-adjustment system of the printing mask, which continuously checks the ECA deposition and

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automatically adjusts the printing station if necessary, eliminating the need for an operator. This ECA deposition is carried out at two independent printing stations, which has the advantage of optimization of the printing if the sunny side/back side of the cell have different requirements. Independent printing will simplify the printing process configuration, and hence reduce related machine downtime.

The positioning of the ribbon/wire on the cell is also more precise as a result of better controlled handling. A relative positioning precision of $100\mu\text{m}$ of the wire/ribbon with respect to the bus can be achieved, enabling easier process control and a more reliable connection.

For the first stencil-process qualification, a $50\mu\text{m}$ -thick stencil was chosen on the front, while a $70\mu\text{m}$ -thick stencil was chosen on the back; the thicker stencil is necessary on the back because of robustness and front-side textured ribbons, which demands thicker ECA to enhance the adhesion. Fig. 4 shows a comparison of screen and stencil deposition mass on the front and back sides of the half-size M2 cell, at the beginning and end of the daily string production (after 6,000 prints). Stencil printing uses less ECA than screen printing, mostly on the front side (4mg less), because of the smaller thickness of the front stencil mask. The authors believe that it will be possible to further reduce this deposit thickness by 50%. No difference is observed in the weight deposited at the beginning of the production and at the end.

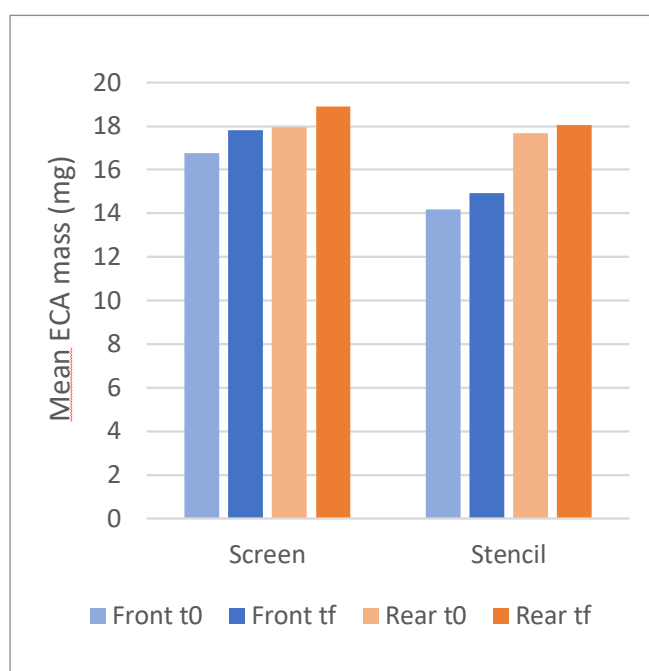


Figure 4. ECA mass analysis (half-size M2 cell).

Fig. 5 shows a comparison of peel forces for screen and stencil ECA deposition on the front and back, and at the beginning and end of the string production. It can be observed that the peel forces are still equivalent for both technologies, at around 0.8 to 1N/mm for the rear side and 1.2N/mm for the front side.

From the work carried out at CEA-INES, the following can be concluded:

- Solar cell stencil printing is not the same as SMT stencil printing: lessons can be learnt, but SMT cannot just be copied.
- For an optimal mechanical holding of the stencil, only separated pads can be printed, not continuous lines. Cell metallization design has to be compatible and optimized for correct mechanical adhesion and reduced electrical conductivity losses.
- For improved aspect ratio printing, beneficial specifications for stencils are demonstrated as compared to screens.
- Simpler printing (lower pressure), with better ECA transfer and release, was identified with stencil printing.
- Higher throughput is possible with stencil printing because of the 'back and forth' process.
- After more than 35,000 prints, no issues in terms of print quality were noticed with stencil printing.
- Stencil printing has high durability and robustness, as cell breakages did not cause stencil breakage.

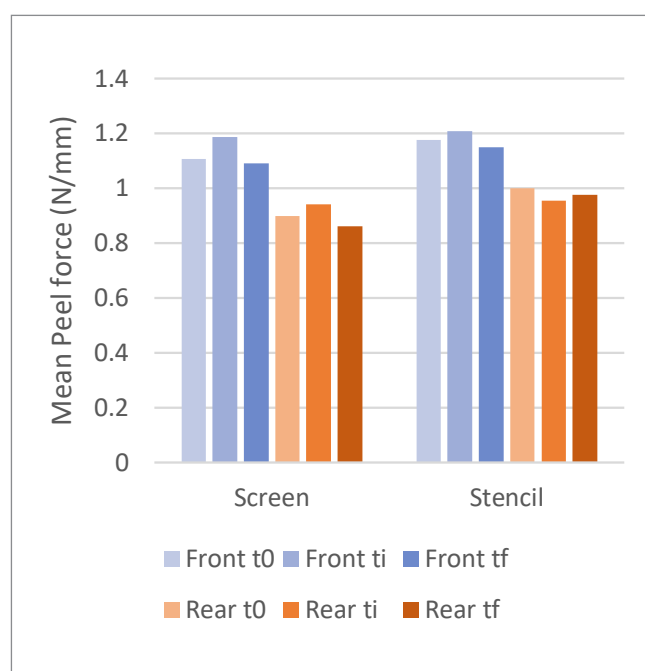


Figure 5. Peel force analysis.

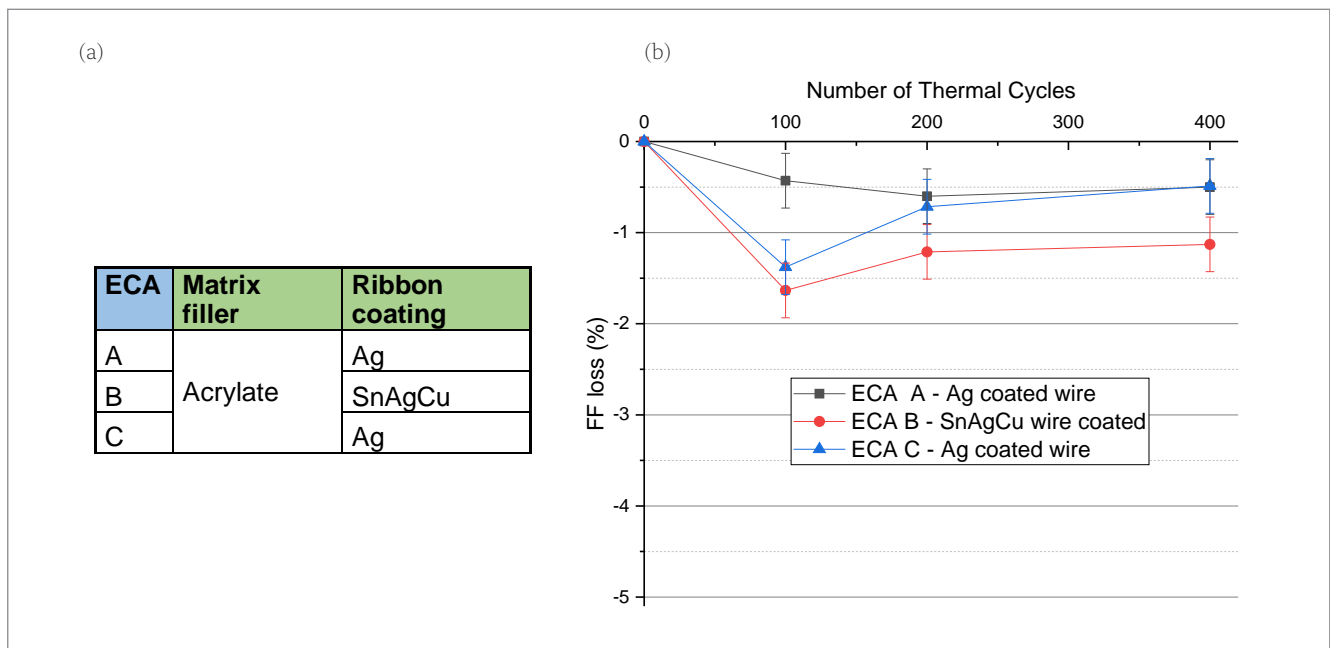


Figure 6. Fill factor (FF) loss after 100, 200 and 400 thermal cycles (-40°C to $+85^{\circ}\text{C}$) for a variety of ECAs with different wire coatings (pads B design/width 1/45% reduction in Ag consumption).

- Stencil printing allows a 10% reduction in the weight of the deposited ECA. This reduction can be further increased with the use of thinner metal plates.

Going further with Ag consumption reduction using new ECA formulations

As illustrated in Fig. 1, ECA reduction appears to be reaching a limit with just the optimization of the deposition parameters. With increases in wafer size, coupled with the consequent increase in the number of BBs, a reduction of the amount of ECA per BB will not be sufficient to achieve a silver target of less than 5mg/W.

Several approaches can be taken to further reduce the amount of silver. The first is a direct silver reduction inside the ECA mixture by the introduction of other conductive particles, such as copper, aluminium or something else, which seems the obvious thing to do. However, silver is quite difficult to replace if one wants to keep the same performance and reliability. Thus, engineering the ECA composition with additives to avoid oxidation and/or to enhance the conductivity of the material is necessary. Material research with a potentially significant impact on Ag reduction is ongoing, and the first formulations are in the qualification stage.

Another important way to reduce silver usage inside the module is to use ECA that is compatible with all types of ribbon coating. Indeed, ECA is usually compatible with silver-coated ribbons; yet, even considering low coating thicknesses ($<2\mu\text{m}$), it is an important silver consumption item ($>30\text{mg}$ per half-cell). This line of approach is currently under investigation, and it is now possible to find a large variety of ECA designed for PV applications among each silver paste manufacturer. Fig. 6 shows a comparison of different ECAs with two types of

ribbon coating. After 400 thermal cycles, a small loss in FF (about 1%) can be observed when combining a specific adhesive with SnAgCu coated wires. It can be concluded that different ECAs that are compliant with the IEC 61215 norm are now available on the market, whatever the ribbon coating used. The number of qualified ECAs should quickly increase, along with their availability on the market.

Module prototyping: results of the production of 400 HJT modules and 6,000 strings with stencil printing

Modules totalling 125kWh were produced for the final qualification of reduced ECA deposition, stencil printing and Mondragon ECA interconnection equipment within the H2020 European project GOPV [14]. These modules integrate the latest developments carried out during the entire project. Thus, material reduction – such as silver, silicon and encapsulant – or reduction of ribbon thickness was performed to lower the final LCOE. The latest architecture optimization also was selected in order to improve the electrical properties of the produced module.

To achieve the goal of realizing 125kWh, 400 modules were produced, which will be monitored in a large field using a fixed- and a one-axis tracker. String manufacturing was performed using the automated Mondragon ECA tabber-stringer. To reduce the ECA consumption, a pad design that cuts the amount of ECA by 45% in weight was selected. Screen- and stencil-printing technologies were used for string manufacturing without any impact on the final reliability. The fabricated strings showed good adhesion ($>1\text{N/mm}$) and very reproducible dimensional aspects, such as inter-cell distance, bending effect and total length. Adhesion remained very stable throughout the production. In all, 6,000 strings were manufactured for the module production.

	V_{oc} [V]	P_{max} [W]	V_{max} [V]	I_{max} [A]	I_{sc} [A]	FF
Min	52.09	360.15	42.95	8.30	8.75	0.77
Max	53.22	369.49	44.28	8.42	8.91	0.79
Standard deviation	0.16	1.92	0.22	0.02	0.02	0.00
Mean	52.69	364.96	43.66	8.36	8.86	0.78

Table 1. Electrical data for the 400 modules.

Modules were partially produced manually, as the quantity of modules was quite low, and so it was difficult to dedicate a production line just for this production. Following the qualification of the BOM, a glass–glass architecture with a polyolefin elastomer (POE) encapsulant (sourced from Europe) was chosen.

The lamination process was performed using a membrane laminator. An aluminium frame was used to reduce the pinching effects that are usually present at the module corners in such a glass–glass configuration. A lamination recipe optimization was carried out in order to achieve optimal glass to encapsulant adhesion and encapsulant cross-linking rate, with a particular focus on final reliability. A total of 400 modules were manufactured, with a very low rejection rate (<5%), considering the manual operations.

Table 1 shows the electrical data for the 400 SHJ modules of 363.5 ± 1.9 Wp with highly reproducible electrical module parameters. These results highlight the process quality and control, at both cell and module material levels.

Stringing development for tandem PK/Si cells

Tandem cells of various configurations are today on the agenda of many research teams all around the world. The technology is interesting and promising, as it seeks to overcome the theoretical limits for single-cell efficiency (~30%). Perovskite tandem hybrid cells have already proved to

be quite efficient and low cost, owing to the inexpensive materials used.

A major issue with the perovskite subcell is that it suffers from severe degradation when exposed to temperatures above 130°C for long durations, limiting the possibility of using high-temperature soldering processes for the stringing. Because of its simplicity and cost effectiveness, screen printing of silver-containing low-temperature pastes will be used first for the metallization in industrial production. It has been shown that the weak adhesion for such pastes (busbars) on the wafer, combined with the fact that the lowest liquidus temperature is 139°C for the metal alloy ($\text{Sn}_{42}\text{Bi}_{57}\text{Ag}_1$), means that the stringing of such cells is not possible using a soldering process. Consequently, interconnection using ECA will be the most suitable technology for such very low temperature cells.

Following CEA-INES's development sequence, the thermal characteristics of the ECA were measured first by DSC. The initial study consisted of determining the maximum temperature of cross-linking of two different commercial ECAs. Fig. 7 indicates the heat flow into or out of two ECA samples as a function of temperature after several heating/cooling cycles. This cross-linking peak is exothermic and the phenomenon is irreversible; in other words, the material once cross-linked cannot change its state and remains hard and rigid. The study was carried out with a heating rate of 10°C/min.

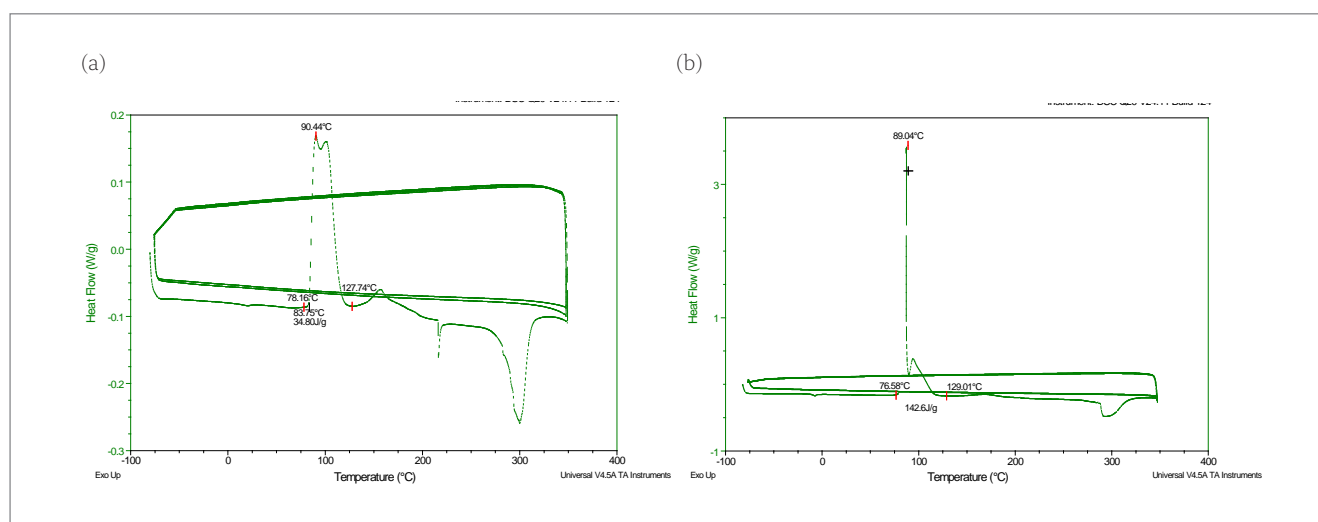


Figure 7. Comparison of heat flow vs. temperature for two different ECAs: (a) DSC analysis of ECA A; (b) DSC analysis of ECA B.

A comparison of the two ECA printing samples shows that the one where the temperature at the maximum of the cross-linking peak is lower will take less time to cross-link at a given temperature than the one where the temperature at the maximum of the cross-linking peak is higher. To reduce the curing time, it is therefore interesting to move towards ECAs whose temperature at the maximum of the cross-linking peak is fairly low. For each manufactured string, several adhesion tests were conducted using a peel force tester at a 180° angle on the bus of the cells. Table 2 presents the results of the peeling tests that were performed on the six busbars present on the front and on the back of the cells, at three different temperatures around 130°C. The result obtained represents the mean value of the measurements taken along the bus.

The peel force test results are not in agreement with the DSC results. According to DSC, it seems that ECA B is more adapted to low-temperature processes than ECA A. The cross-linking temperature differences are, however, relatively small, and the better peel force for ECA A can be attributed more to its higher Ag content.

It can be concluded that sufficient adhesion ($>0.8\text{N/mm}$) is obtained with both types of adhesive, cured at temperatures below 130°C. This realization highlights the capacity of the ECA tabber-stringer to interconnect different kinds of cell using very low temperature processes. Further reliability testing of these ECAs is currently under way.

New equipment and processes for HJT and tandem perovskite/silicon cells

Mondragon Assembly has already launched its high-precision tabber-stringer machine with ECA technology for HJT high-efficiency cell technology, and is capable of producing up to 2,600 HJT cells per hour (Fig. 8). For this new development, which comes with independent printing of both sides of the cells, flexibility is a key aspect of this machine, since it can produce strings of up to 15 busbars with cell sizes of up to G12 (210mm × 210mm) in full-, half- or third-cell

Temperature	Front side [N/mm]		Back side [N/mm]	
	ECA A	ECA B	ECA A	ECA B
120	1.3	1.0	1.0	0.7
130	1.5	1.2	1.2	0.8
140	1.7	1.2	1.3	1.0

Table 2. Peel forces after the manufacture of the strings (before lamination).

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format. In addition, it is able to handle cells as thin as 110µm, and is also compatible with gapless and paving technologies. With regard to the interconnection elements that can be handled by the machine, ribbons as narrow as 0.2mm × 0.5mm and wires down to 0.25mm in diameter can be accommodated.

Thanks to the numerous visual controls that have been installed after each step of the process, this new machine guarantees a high precision and quality of the manufactured strings; this allows the efficiency of the machine to be increased and better manufacturing results to be obtained in less time. In order to increase the available uptime of the machine, the equipment includes a cleaning station to assure continuous printing, as well as straightforward filling because of the open lay-out of the printing stations.

However, the developments and commitment made by Mondragon Assembly go a step further: jointly with CEA-INES, the development of a multi-busbar wire-soldering solution for HJT is also in progress.

Conclusion

To avoid severe deterioration of the surface passivation of a SHJ cell due to the degradation of



Figure 8. The MTS-ECA (MTS1105-1) stringer.

its surface passivation properties, interconnection processes are limited to temperatures below 200°C. ECA-based interconnections have various advantages inherited from the family of adhesives, such as low toxicity (no lead), tolerance towards mechanical deformation, and low processing temperatures (between 120°C and 200°C, compared with 250°C for standard lead-free solder). The latter property is critical to reducing the thermomechanical stress within the wafer, and makes the ECA type of interconnection suitable for thin wafers and/or future silicon/perovskite tandem cells.

At CEA-INES, a sequential qualification process has been developed to evaluate the PV performance of ECA-based stringing processes. First, the process window of the ECA is assessed using DSC. Based on this input, a process optimization on the ECA-based stringer is begun in order to determine the screen- or stencil-printing parameters for the ECA deposition and curing conditions with direct heat or IR heating. The fast-feedback method of adhesion measurement of the ribbons on the cells assists the process optimization, aiming for a minimum value of between 0.5 and 1N/mm in a 180° peel-test configuration.

The sustainability of PV production on a TW scale requires examination of the availability of scarce materials, with the main concern being Ag usage, as already 10% of the global supply was directed to PV in 2020. It is essential that Ag consumption is drastically reduced in the future if PV is to be sustainable. Taking into account the upcoming increase in wafer size and the use of multiple ribbons, four main options for Ag reduction at the interconnection level were proposed and discussed.

Excellent reliability, with less than 1% loss in fill factor, over 400 thermal cycles was obtained when the deposited weight of ECA was reduced to 45% (11mg/W). The use of SnAgCu -coated ribbon associated with adapted ECA allowed further reductions in the amount of silver coating used, to 4mg/W. A decrease of less than 1.2% in fill factor was observed after 400 thermal cycles with this low-Ag process. The authors believe that the use of silver can be decreased still further by employing thinner stencil plates and ribbons without any silver coating at all.

Mondragon Assembly recently developed an industrial ECA tabber-stringer – the ECA-MTS – for the ECA interconnection of high-efficiency cells, as a result of productive work within the framework of the European-funded GOPV project. The improved accuracy of the ECA-MTS means that only a very small quantity of deposited ECA is necessary

to create a reliable interconnection. Accuracy alignments of less than 100µm for ribbons of 0.6mm on ECA lines of less than 300µm in width have been demonstrated. Moreover, the use of a stencil instead of a mesh screen improves the alignment as a result of less screen deformation and better reproducibility of the deposit during the processing time. More accurate positioning of the ribbon will also affect the metallization design – another way to limit Ag usage at the cell level.

Tandem cells of various configurations are currently on the agenda of many research teams worldwide. Perovskite tandem hybrid cells have already proved to be quite efficient and low cost, mostly because of the inexpensive materials used. A major issue with the perovskite subcell, however, is that it degrades severely when exposed to temperatures above 130°C for long durations; this limits the possibility of using high-temperature soldering processes for the stringing. Because of its simplicity and cost effectiveness, screen printing of silver-containing low-temperature pastes will be used first for the metallization in industrial production. It has been shown that the weak adhesion associated with such pastes (busbars) on the wafer, combined with the fact that the lowest liquidus temperature is 139°C for the metal alloy (Sn₄₂Bi₅₇Ag₁), makes the stringing of such cells not possible using a soldering process. Consequently, interconnection with ECA will be the technology most suited to such very low temperature cells.

It was demonstrated that sufficient adhesion (>0.8N/mm) was obtained with two different types of ECA adhesive, cured at temperatures below 130°C. This outcome highlights the capacity of the ECA tabber-stringer to interconnect different kinds of cell with very low temperature processes.

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