INTERCONNECTION TECHNOLOGY FOR THE NEXT GENERATION OF (TEMPERATURE-SENSITIVE) SOLAR CELLS SUCH AS HETEROJUNCTION AND C-SI/PEROVSKITE TANDEM

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ABSTRACT: The interconnection technology for solar cells is an important component in the PV module production - not only for module reliability but with respect to the sustainability of the PV industry as well. We are proposing the interconnection technology “TECC Wire” (TECC=Thermoplastically and Electrically Conductive Coating) which is a new low-temperature method – and which avoids the usage of any rare or hazardous materials. As rare or critical materials in the PV industry are rated such as silver, bismuth, lead and indium because global resources are considered to be too limited or too expensive for the terawatt production level. And the usage of lead does not comply with the RoHS (Restriction of Hazardous Substances) directive. Although PV modules are still exempt from this directive, efforts to avoid using lead as a solder alloy are consensus in the industry.

TECC-Wire is conceptually an improved stage of the multi-busbar or multi-wire concept. However, it allows to further reduce the consumption of silver for the solar cells metallization, and it even enables the vision of totally eliminating silver from solar cell production. The TECC wires have a similar copper core that is typically used for multi-busbar soldering of solar cell – but it is coated with an electrically conductive adhesive instead of a solder alloy. The filler material to achieve the electrical conductivity is based on non-silver particles.

The recently built semi-automated stringing machine attaches the TECC wires precisely and in a defined manner. It allows us to build and test standard module configurations. The long-term reliability tests have already passed 3x IEC requirement. After 3000h damp heat test the degradation of the small modules is below 5%. In thermal cycling test the results after TC600 are around 5% for different solar cells. The peel strength is about 1.5 N/mm contact area over the entire solar cell – which is comparable to a solder joints. The homogeneity of the peel strength along the entire surface of the solar cells is remarkable, as the wires adhere to any surface and not only to the printed fingers.

Keywords: Module, Metallization, Low-temperature, Heterojunction

1 INTRODUCTION

Passivated c-Si solar cell technologies such as PERC (Passivated Emitter and Rear Cell) and TOPCon (Tunnel Oxide Passivated Contact) will continue to dominate the market. However, new technologies for higher conversion efficiencies will gain market share. As early as 2024, HJT's (heterojunction technology) share will already be 10%, and by 2032 it will reach 20% market share [1]. Si-based tandem technologies will play a role in mass production beginning from 2024 [1]. The main challenges for HJT in mass production are the enormous silver consumption for the solar cell metallization, the use of rare and expensive indium as TCO (transparent conductive oxide) layer and the necessary low-temperature contacting using tin-bismuth alloy– because HJT solar cells have to be processed at low temperatures <200°C [2], whereas common solar cells such as PERC and TOPCon can be processed and soldered at significantly higher temperatures. In addition to cost and processing concerns, the global deposits of silver, indium and bismuth will conceptually limit the growth of the PV industry in general if no replacements of those critical materials can be established [2].

2 WHAT ARE THE PROPOSED APPROACHES IN THE PV INDUSTRY?

2.1 Reduction silver consumption

Compared to the PERC, the HJT solar cell consumes about twice as much silver [1]. Increasing the number of BBs (busbars) has proven to be an effective means to reduce solar cell paste consumption. While the 12BB layout is already implemented, the industry has begun to increase the BBs up to 16, with some even planning to go more than 18 [3]. As an example, the so-called “SmartWire” technology by Meyer Burger, which contacts busbar-less HJT solar cells, has the lowest silver consumption for screen printed HJT [4]. This is exclusively due to the number of wires and the busbar-less solar cells – up to 22 solder wires are used. However, the technology is no longer available for the market since Meyer Burger claims the technology to be used only for its own module production.

A promising saving potential is to replace silver with copper. Copper plating technologies (with seed layers) have been discussed and tested in the industry for some time – but except for the short period of First Solar´s “Tetrasun” product in 2015/2016 [5] it has not found approval in the PV industry for series production. What is also currently being intensively tested for HJT solar cells is to use metallization pastes with silver-coated copper particle instead of pure silver. Recently a record efficiency of 25.62% on M6 wafers using silver-coated copper pastes has been reported [6]. According to the report it can reduce the silver consumption of the HJT solar cells by 55%. A second approach is to have pure copper pastes and replace silver completely. However, the potential oxidation of the copper surface is a risk factor for reliability, but such HJT solar cells are subject of current R&D. We have recently started the testing of applying the “TECC-Wire” technology to such silver-free solar cells.

2.2 Reduction of indium consumption

Indium is not only very expensive but also belongs to the rare materials. However, indium tin oxide (ITO) is currently the best material for transparent conductive oxide (TCO) layers for HJT solar cells. There are some approaches to replace ITO e.g. by AZO (aluminum zinc oxide) but module reliability is still not sufficient with pure AZO as TCO. A promising approach is the multi-layer TCO with AZO as the bulk material and ITO just as a cap layer. This approach is already delivering promising reliability results and would at least significantly reduce the consumption of indium.

2.3 Bismuth in solder alloys

Bismuth is used as a low-temperature solder alloy for the interconnection of HJT solar cells. As mentioned above bismuth is considered as a critical and limited raw material. In addition, bismuth as a lead substitute is very controversial and was not implemented in the electronics industry when converting to lead-free solder within the framework of the ROHS directive. Currently there is no substitute material for bismuth available for low-temperature soldering, and only a gluing technology can avoid the usage of bismuth.

3. PROPOSED SOLUTION: TECC-Wire

This technology was introduced in 2021 [7]. It bases on copper wires with an electrically conductive thermoplastic coating. It is a low temperature interconnection technology because the melting point of the coating can be engineered in a range between 130°C - 180°C. The technology does not use any rare or critical material such as Ag, Bi or Pb and thus it is fully compliant with the ROHS directive. Since it is a gluing technology, the wires stick to any surface and thus enable the use of busbar-less solar cells with respective savings in silver consumption.

Additional advantages of the "TECC-Wire" technology are:

- there is no limitation to the number of wires used per solar cell. It can use any number of wires – enable reduction of silver consumption
- It does not require any solderable electrical contact surface. It opens the vision to eliminate silver from the solar cells by using very alternative metallization strategies
- No flux is required. Flux is not only "dirty" in module production – but also potential risk factor for field degradation
- Simplification of wire positioning accuracy, since no busbars are required

4. SAMPLE PREPARATION

The semi-automated stringing lab equipment enables to place the wires in a defined manner. Although the stringing machine is still in a lab configuration, it is possible to build strings for full-size modules. Figure 1 shows the semi-automated stinging machine and a full string of half-cut M6 HJT solar cells coming out of the machine.

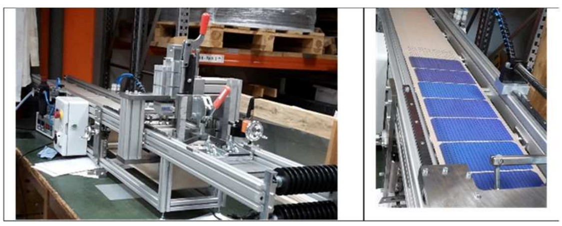

Figure 1: Semi-automated TEEC-Wire solar cells stringing machine (left), and a full string of half-cut M6 HJT busbar-less solar cells

A full-size module is demonstrated in figure 2. It shows a photo of the module front side (left) and the respective EL image (right). The solar cells are half-cut M6 HJT. Apart from a few minor cracks the EL image is very homogeneous. The cracks appear along the solder joints of the cross-connectors. It shows that more attention when connecting the strings has to been taken by the lab team. The EL image is taken at a current of 9A applied for 1sec.

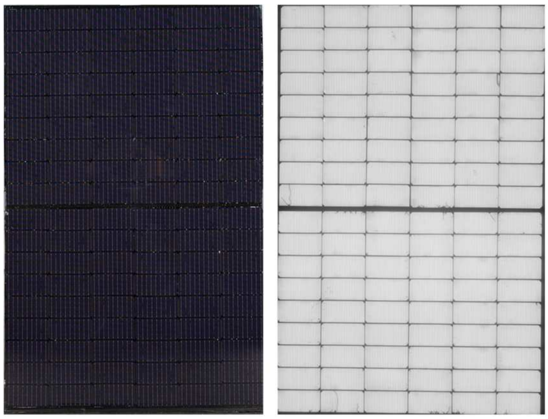

Figure 2: Full-size glass/glass module with butyl edge sealant – front side photo (left) and EL image (right; 1sec @9A). The module was built using the semi-automated TECC wire stringing machine with half-cut M6 HJT solar cells.

5. RESULT AND DISCUSSION

5.1 Peel strength

Figure 3 is showing the peel strength data of busbar-less M6 half-cut HJT solar cell connected using TECC wires. The peel strength test is done using Zwick/Roell machine with a pull angle of 180° and a testing speed of 200mm/min. The measurement results are exemplary for all measured solar cells. The M6 half-cut solar cell was contacted with 16 TEEC wires. The figure shows four wires peeled off from the front side and from the back side, respectively.

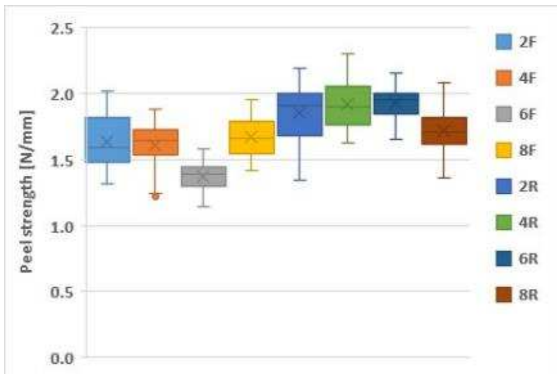

Figure 3: Peel strength of busbar-less M6 half-cut HJT solar cells – e.g., 2 stands for wire No. 2, F for front and R for rear side of the solar cell

What is clearly evident from the boxplot – maximum, minimum, and average value are shown - that no wire adhesion force anywhere gets even close to 0N over the entire solar cell contact area. This demonstrates that the wires stick very well both onto the finger grid as well as onto the solar cell (TCO). The minimum peel strength is always well above 1N/mm contact area, which is comparable to soldering of HJT solar cells with busars [8]. Although the "TECC-Wire" connection technology is more comparable to gluing rather than soldering, we are referencing to the more established data for solar cell soldering technology.

5.2 Damp heat (DH) results

The recent DH test results were made with 1-cell modules (coupons) of M2 HJT solar cells. Some solar cells have been contacted by ECA (Electrically Conductive Adhesives) as reference, and others from the same batch with the "TECC-Wire" interconnection technology. The aim was to compare the TECC wires with the state-of-the-art interconnection technology for HJT solar cells. The solar cells where then encapsulated in glass/backsheet technology, with a POE as encapsulant and a backsheet with moisture barrier.

Figure 4 is showing the results of the ECA and with TECC wires connected coupons after DH3000 – which is equivalent to 3x IEC standards. The data points are the average value for 3 test samples. The power degradation after DH3000 for the ECA coupons is below 2% which is very good results for HJT modules. The "TECC-Wire" coupons reliability is slightly worse to those ECA contacted samples. However, after DH3000 the degradation is around 5% which is still a very good value.

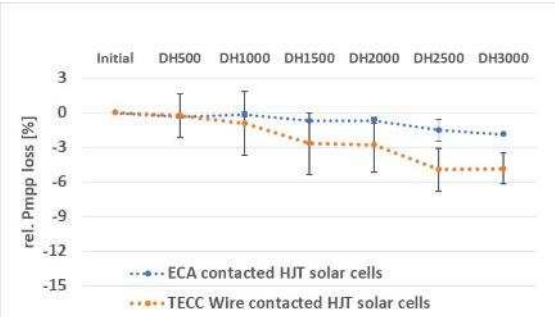

Figure 4: M2 HJT solar cell coupons connected with electrically conductive adhesives (ECA) as reference and the TECC-Wire technology after DH3000. The coupons were encapsulated using a backsheet with moisture barrier

5.3 Thermal cycling (TC) test

With respect to the long-term reliability of a PV module, thermal cycling (TC) is the hardest test to assess the interconnection technology. Using the semi-automated stringing machine and after process optimization, we have reached very good results and even passed 3x the typical IEC requirement. The degradation is below 5% after TC600. Figure 5 is illustrating the results. The M2 HJT solar cells were contacted by using the semi-automated stringing machine, and were then encapsulated in glass/glass technology to 1-cell coupons. The data in figure 5 is showing relative degradation to initial STC (Standard Test Conditions) power measurement.

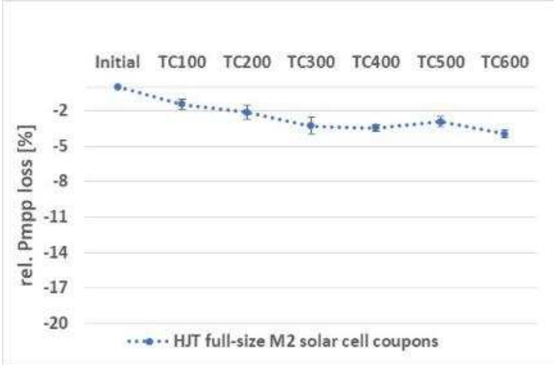

Figure 5: Thermal cycling (TC) test of solar cell coupons (1-cell modules) contacted using TECC wires. Busbar-less M2 HJT solar cells were used, and 22 TECC wires were applied. The data points show an average of min. 10 samples.

6 SUMMARY AND OUTLOOK

New high-efficiency solar cell technologies such as HJT and also c-Si/Perovskite tandems are pushing into the market and will gain market share over the next decade. Currently the PV industry is facing the dilemma that these new technologies i) make solar cells temperature-sensitive and ii) require an increased consumption of critical materials. Critical elements are expensive elements with limited resources such as silver, indium and bismuth. At the same time the PV industry is striving and is forced to minimize consumption of critical elements – which otherwise could slow down the industry's growth to terawatt production level.

The solar cell interconnection technology in PV module production has always been a key process for product quality and reliability, but recently it has become even more important as the interconnection technology determines the solar cell design and thus the usage of critical materials. It decides if lead and/or bismuth is used, and how much silver is consumed for the solar cell grid printing and eventually for ECA.

Having a suitable solar cell interconnection technology is a key factor to introduce new high-efficiency solar cell technologies - and at the same time to reduce the consumption or even eliminate critical materials for the PV industry.

The "TECC-Wire" technology is a very promising approach to meet all future technical and commercial requirements. It is not using lead or bismuth or indium or silver for the wire coating, and it allows low process temperatures which even can be tuned in a range between 130 – 180°C. Additionally it allows a busbarless design for the solar cell front grid, leading to a reduction of silver consumption for the solar cell production. Since it does not require a solderable surface but it achieves a very good mechanical and electrical contact to any surface, it may allow totally new metallization strategies which bases on copper or aluminum or nickel or other cheap metals.

In this paper we have shown reliability test results, and for small modules we have already passed 3x IEC standard requirements with degradation rates below 5%. The results in DH and TC are comparable to small modules made with ECA as a reference technology. The peel strength value of the wires to busbar-less HJT solar cells is above 1 N/mm contact area over the entire solar cell which is comparable to soldered HJT solar cells.

Full-size modules have also been built and will be subject to further extended laboratory testing to verify the long-term reliability of the TECC-Wire technology. One full-size module is already in outdoor testing where the energy yield and possible degradations are monitored in comparison to several commercial products.

7 ACKNOWLEDGMENT

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