Thermoplastically and Electrically Conductive Coated Wire for the Interconnection of Temperature-Sensitive Solar Cells

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***Abstract*—In this paper we are reporting a new approach by using thermoplastically and electrically conductive coated wires (so-called TECC wires) to interconnect solar cells – it is a modified multi-wire technology. The typical process temperature range is 130°C – 180°C which makes it suitable for temperature sensitive solar cells such as silicon heterojunction (SHJ) or silicon-perovskite tandem solar cells. The wires consist out of a round copper core with a diameter of 280 µm which is covered by a very thin layer of silver for corrosion protection, and then surrounded by about 40 µm coating of an electrically conductive thermoplastic material. As many as required wires can be applied on the busbar-less solar cells.**

Keywords— multi-wire, thermoplastic, ECA, Heterojunction solar cells, busbar-less, TECC-Wire, gluing

I. INTRODUCTION

Soldering based on the multi-wire concept is a well-established and well understood technology for the interconnection of solar cells [1]. However, it is still a challenge to interconnect new types of solar cells that are pushing into the market such as silicon heterojunction (SHJ) and c-Si/perovskite-tandem solar cells. The temperature sensitivity of those solar cells is a critical factor which prevents from using standard soldering techniques. There are low-temperature soldering options but Ag pastes for being printed on the SHJ solar cells need to be optimized (for soldering quality and for low consumption as well) and additionally the low-temperature solder alloys tin-indium or tin-bismuth are not established in other industries although they are RoHS (Restriction of Hazardous Substances) compliant. Additionally, there are concerns about the long-term stability of bismuth, and indium-based alloys are simply too expensive for mass-application. In addition, the use of bismuth as a lead substitute is generally not recommended for reasons of product quality, recycling, sustainability, environmental and health aspects as well as for economic reasons [2]. Further, interconnection technologies such as *"SmartWire"* or low-temperature soldering on multi-wire approach using bismuth alloy also pose a major risk for Terawatt level annual PV production [3]. Similar to indium, bismuth is also a limited resource. *"SmartWire"* interconnection technology has the potential to become the standard technology of SHJ modules – however, it is important to assess the sustainability aspect of using bismuth before scaling [3].

Following the automotive industry which has agreed to change to RoHS compliant alloys such as SnAg or SnAgCu is not an option for the solar industry because those alloys have even higher soldering temperature than the lead-based solder alloys which are currently common in the PV industry. One potential direction is to substitute soldering by using electrically conductive adhesives – but this approach comes with its own challenges and disadvantages. For now, the perfect interconnection technology for temperature-sensitive solar cells still needs to be determined.

II. WHAT IS OFFERED ON THE MARKET TO INTERCONNECT SHJ SOLAR CELLS?

The *"SmartWire"* technology from the Swiss-based company Meyer Burger has been the option of choice for several SHJ manufacturers [4]. However, Meyer Burger has announced that the technology will be exclusively used for its own module products in future [5, 6]. This comes with the change in strategy of the Meyer Burger group to become a solar cell and module manufacturer rather than being an equipment supplier for the solar industry. Therefore the *"SmartWire"* technology is not a widely accessible technology option anymore.

Electrically conductive adhesives and conductive films are also offered as an option, and both are commercially used, too. The advantage of these solutions is that no busbar print on the solar cell is necessary which means a drastic reduction of Ag-paste consumption. However, the additional costs associated with conductive adhesives – which are also silver-filled – eliminate this benefit [7]. In addition, working with more than five busbars with conductive adhesives is difficult to manage for cost and handling reasons. As demonstrated in [8], all investigations into industrializing heterojunction solar cell interconnection by applying an electrically conductive adhesive instead of soldering were carried out with a typical stringer using four busbar solar cells.

At this moment low-temperature soldering is the most widely used method to interconnect SHJ solar cells – because this has been an approach with a fairly easy implementation into mass production [7]. However, it is not the ideal solution, and especially for c-Si/perovskite tandem cells it might not work at all because the perovskite layers seem to be extremely temperature-sensitive.

III. WHAT IS THE INDUSTRY LOOKING FOR?

Due to the above described circumstances the PV industry is looking for alternative technologies. Ideally it should work in a temperature range < 200°C and similarly to multi-wire technology – and with low use of any hazardous or rare or expensive material –. Silver consumption in solar cell production is a major concern for the industry. The lowest expected silver consumption in 2030 for PERC is 8.3 mg/W – TopCon and SHJ consume even more silver [3]. At that level, production of one (1) terawatt PERC solar panels would consume approximately 30% of the global silver supply [3] which is not a viable scenario. However, no solution based on electrically conductive adhesives has been able to provide this demand from the industry. We expect great interest from the industry for a solution which can combine the advantages of conductive adhesives and multi-wire interconnection approach, and at the same time does not use any critical material.

IV. WHAT IS THE APPROACH OF THIS INVESTIGATION?

The new approach is to use thermoplastically and electrically conductive coated wires (TECC wires) to interconnect solar cells based on multi-wire technology [9]. Those wires can be directly attached onto the busbar-less cells. Depending on the number of wires the solar cell´s grid finger distance and thickness can be optimized. The TECC-Wire technology is an innovative approach for reducing silver consumption or have even silver-free solar cells because the wires can be mechanically and electrically connected to almost any surface of solar cells.

The benefit is to enable a multi-wire solar cell interconnection at low temperatures without soldering. The typical process temperature for the currently used TECC-Wire is 150°C – 180°C. However, conceptually it can be adjusted according to the needs by modifying the coating with thermoplastic base resins with different glass transition temperatures which will make the TECC-Wire technology suitable also for c-Si/perovskite tandem solar cells. We expect that it will be possible to develop a set of raw materials to keep all module production process steps even below 130°C (if required). Modified commercial stringing equipment is supposed to be suitable, making implementation into series production fairly easy.

V. EXPERIMENTAL SETUP

For the proof-of-concept 1-cell coupons were manufactured with different types of solar cells. The solar cells got contacted with different interconnection methods, and we compared the TECC-Wire technology to other means of interconnection with respect to current, voltage, fill factor and power.

The TECC wires consist out of a round copper core with a diameter of 280 µm which is covered by a very thin layer of silver for corrosion protection, and then surrounded by a 40 µm coating of an electrically conductive thermoplastic. Melting temperature of the coating was 150°C. No automated machine was available for the first proof of concept test results, and the application of the wires to the solar cell was done fully manually with respective inconsistencies. Recently we have constructed a semi-automated stringing machine which allows to attach the wires more precisely and in defined manner. Figure 1 illustrate the first string of busbar-less SHJ solar cells contacted with TECC-Wire by the semi-automated stringing machine. Basically, we now have the option of building even a full-size standard module with square or half-cut solar cells.

Figure 1: First string of busbar-less SHJ solar cells connected by TECC-Wire produced by a semi-automated lab-scale stringing machine

The contacted solar cells are laminated using a standard industry laminator and regular commercial solar module materials (encapsulant, glass and backsheet). The 1-cell coupons were then analyzed by EL and IV-curve measurements.

VI. RESULTS AND DISCUSSIONS

So far, we have been focused on the feasibility of this new solar cell interconnection technology. Nor the TECC-Wire itself neither the application process are technically optimized. Nevertheless, the results are very promising, as will be shown in detail below:

A. *9BB half-cut PERC solar cells*

The very first trials of the technology had been done 3 years ago with conventional 3BB solar cells. Basically, identical electrical data compared to conventional soldering had been achieved.

A recent experiment with commercial 9BB PERC half-cut solar cells gave a slightly higher current and lower fill factor for the TECC-Wire technology which both can be attributed to the dimension of the flat wires used for the reference soldered samples. The mechanical bond and the electrical contact are both very good. Fig. 2 shows the EL images of the soldered and by means of TECC-Wire contacted PERC 9BB half-cut solar cells. Table 1 is showing the respective electrical data.

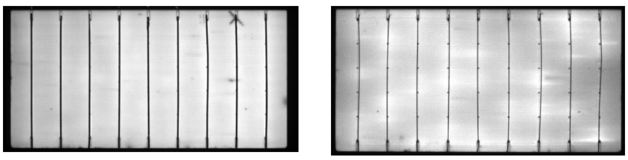


Figure 2: EL images of 9BB solar cells with soldered narrow flat wires (left), and contacted by TECC-Wire technology (right*)*

Table 1: Respective electrical IV-data of 9BB half-cut solar cell

Tests	Voc [V]	Isc [A]	Pmpp [Wp]	FF [%]	Vmpp [V]	Impp [A]
Soldered	0.68	4.61	2.55	81.04	0.58	4.41
TECC-Wire	0.68	4.69	2.47	77.05	0.55	4.48

B. Busbar-less SHJ solar cells

Figure 3 is showing the EL image of a busbar-less SHJ 1-cell coupon which was manufactured by TECC-Wire technology. This is a typical EL image of the first batches of coupons which were manufactured by a semi-automated stringing machine. The wires are positioned fairly evenly but still not perfectly spaced. The EL image is homogeneous over the entire cell area.

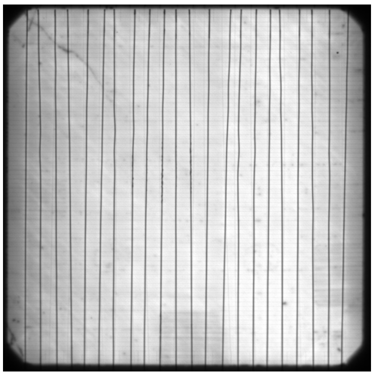


Figure 3: An exemplar of EL image of a busbar-less SHJ 1-cell coupon contacted by TECC-Wire technology. 22 wires are applied on the M2 (156.75 x 156.75 mm²) solar cell

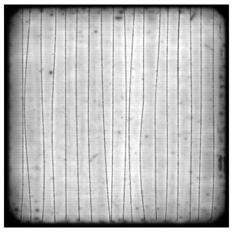
The initial electrical data look pretty good. Table 2 is showing the average IV-data of 5 coupons which were contacted with the TECC-Wire technology. After contacting and encapsulation, current (Isc) and FF are decisive for power (Pmpp) gain and losses since the voltage (Voc) is not affected. The optical loss/gain after encapsulation will determine the Isc. However, more important for the interconnection technology is the FF contribution to the electrical losses. From internal investigation it is known that solar cells with a comparable setup and connected with *"SmartWire"* technology with 22 round wires low temperature melting alloy achieved FFs of approx. 78%. This means the results we have achieved by the TECC-Wire interconnection technology is comparable to the standard interconnection technologies. Unfortunately, we did not have access to any reference technology applied to the exact same SHJ solar cell type (e.g. *"SmartWire"* interconnection). Although this comparison is some kind of „indirect".

Table 2: Electrical IV-data of busbar-less SHJ 1-cell coupon contacted by TECC-Wire interconnection technology.

Tests	Voc [V]	Isc [A]	Pmpp [Wp]	FF [%]	Vmpp [V]	Impp [A]
TECC-Wire	0.73	8.50	4.9	78.5	0.59	8.29

C. Humidity-freeze tests

Very critical of course is the reliability of the solar cell interconnection and we can present initial data for HF10 (10 cycles humidity-freeze) testing of the busbar-less SHJ 1-cell coupons. The cells were interconnected at a temperature of 170°C with good and uniform electrical contact which is proven by the EL image and the electrical data below. This first reliability test by HF10 is showing a decrease in power by 5% but since there is decrease in Voc and Isc and respective indication in the EL image (see Fig. 4, the loss seems to be related to the solar cell itself rather than to the interconnection. The backsheet's water vapor barrier properties may not have been sufficient, leading to a degradation of the solar cell.



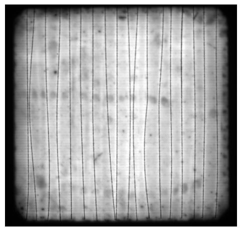


Figure 4: EL images of a TECC-wire contacted 1-cell coupon with a busbar less SHJ solar cell before (left) and after HF10 (right).

Table 3 IV-data of TECC-wire contacted 1-cell coupon with a busbar-less SHJ solar cell initially and after HF10.

Tests	Voc [V]	Isc [A]	Pmpp [Wp]	FF [%]	Vmpp [V]	Impp [A]
Initial	0.73	8.77	4.85	76.04	0.57	8.52
After HF10	0.72	8.70	4.59	72.76	0.56	8.24

D. Thermal cycling tests

Figure 5 shows thermal cycle (TC, test conditions according to IEC 61215) results of busbar-less SHJ solar cell coupons. The solar cells were contacted by TECC-Wire technology, encapsulated in glass / glass one-cell coupon samples, and then tested in TC. The newest coupons are made by the semi-automated machine which was commissioned just recently. These coupons have reached only TC100 until today. The older samples which were made by manual application had been tested till TC600. The diagram is showing an average of 13 coupons for the semi-automated build samples and six for the manually made samples. The standard deviation of the degrade samples is also shown in the diagram.

The readout was made every 100 cycles. The only difference between the two groups (manually and semi-automated made samples) is the application process during TECC-Wire interconnection. All other materials, module building processes, encapsulation, etc. remain the same for both groups. Very noticeable in this diagram is that all samples from the first group (manually made) show the same trends. The first degradation after TC100 is in the range of 7 to 10% depending on the samples, but after this initial loss all samples are very stable up to TC600. We believe that the reason for the loss is that we have slightly damaged the samples or did not contacted them perfectly during sample preparation because of the fully manual process.

For the second group of samples we have used a semi-automated machine which had been built in collaboration with Beuth University in Berlin. This semi-automated machine enables us to apply the TECC-Wires more precisely and in a defined manner. Up to now our focus is still to demonstrate the feasibility of the technology – nothing is yet optimized.

However, the machine helps us to go one step further and identify an application process with defined parameters. The readout of these coupons will also be every 100 cycles. However, this result is a very good indication and provides an interesting comparison to the older, manually made samples. Basically, it confirms our hypothesis that working manually we may have damaged the solar cells when making the coupons or bad contacting. All 13 pieces of recently produced coupons degrade only less than 2%.

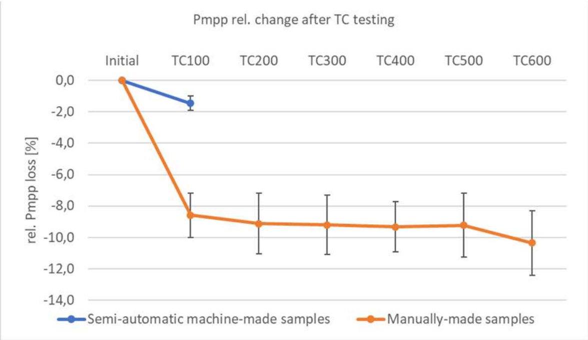


Figure 5: Recent thermal cycle (TC) test results of coupons with busbar-less SHJ solar cell coupons contacted by TECC-Wire interconnection technology and encapsulated into glass / glass coupons. Shown is the STC power degradation after TC and related standard deviation of the tested group of coupons.

A typical EL image from the first group (manually made) of coupons in TC-test is shown in figure 6. It shows the EL image at initial stage, after TC100 and TC600. After TC100 already a clear difference to the initial stage can be observed which means that the first degradation occurred in the first TC100 cycles which is a typical indication for cell damage during the module manufacturing processes. Similar to the Pmpp data (see Fig. 5), the EL images do not indicate any further degradation after TC100 up to TC600, which again illustrates the stability of the electrical interconnection after TC100. Looking very closely at the EL images you can observe that the areas which have been degraded after TC100 – darkening at the edges right and left of the coupon – already appear in the initial stage.

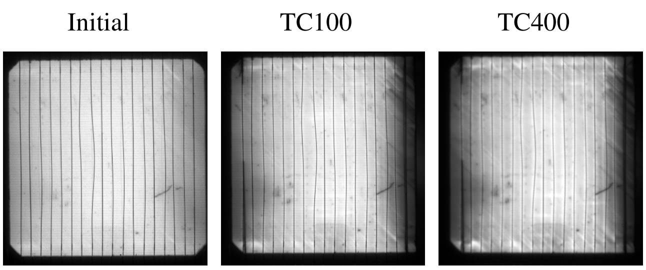


Figure 6: EL images of a manually made one-cell coupon initially, after TC100 and TC600

An exemplary EL image of the second group of coupons (semi-automated machine made) is shown in Figure 7. In contrary to the manually made samples the EL image does not show any indication for a damage. We will continue testing and tracking, but based on previous manually made results we should expect these coupons to remain stable until TC600.

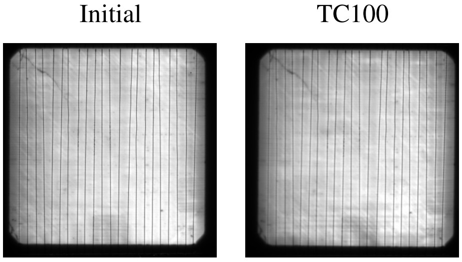


Figure 7: Exemplary EL images of semi-automated machine-made one-cell coupon at initial stage and after TC100. No significant degradation can be observed.

E. Damp heat tests

Figure 8 illustrates resent results of one-cell coupons after 500h of damp heat testing (DH500 test conditions according to IEC 61215). It shows the IV-data degradation for an average of 10 busbar-less SHJ solar cell coupons and the standard deviation. The solar cells have been contacted with the previously mentioned semi-automated stringing machine with TECC wires, and then encapsulated into glass / glass coupons with standard materials using an industrial laminator. The coupons have no edge sealant which could prevent moisture entering from the edges. However, the chosen encapsulant is a commercial cross-linking POE (polyolefine) which has a good water-vapor barrier property. As can be seen in figure 8 most of the degradation is related to FF losses. It is currently not clear whether this is due to the solar cell properties itself or the interconnection technology. We might see a degradation associated with solar cell corrosion since the TECC wires connection looks very similar to the initial stage. However, the test result is promising, and we will continue DH testing.

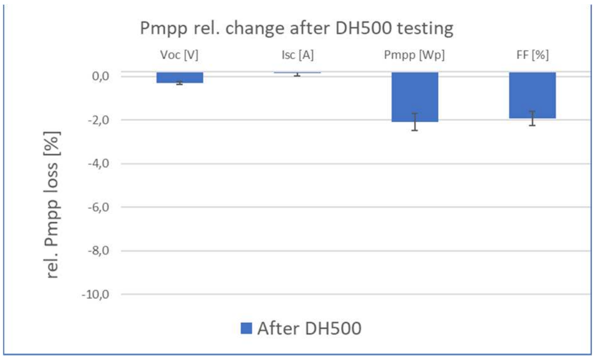


Figure 8: Recent results of DH500 tested coupons which were built using the semi-automated stringing machine. The data show the average of 10 coupons and the standard deviation

The exemplary EL image of a one cell glass / glass coupon after DH500 test is shown in figure 9. The EL image does not indicate any visible degradation mechanism.

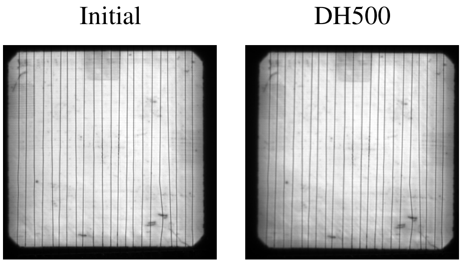


Figure 9: Exemplar EL image of glass / glass coupon encapsulated using industrial materials and laminator. The busbar-less SHJ solar cell are contacted by TECC-Wire with a semi-automated stringing machine

F. First trial run with an industrial multi-wire stringer

We had the opportunity to run trials for the automated application of TECC wires on a commercial high-throughput multi-busbar stringer (model CHn40 by XN Automation). For these very first trials with 12 busbar cells the machine was set up and got equipped with low-temperature soldering wires, coated with an SnBiAg alloy. Two out of the 12 soldering wires then got substituted by TECC wires, and all the tests were conducted with solder wires and TECC wires side-by-side.

Figure 10 is showing some of the results from the first test run. The aim was to check to what extend a commercially available machine can act as a basis for the industrial implementation of the TECC-Wire technology. Several cell types were tested, and Figure 10 shows a PERC solar cell as an example. Due to their dark color the two TECC wires are clearly visible on the rear of the solar cell (left picture). However, on the front of the solar cell (picture on the right) they can hardly be distinguished from the SiBiAg wires. You have to look very closely to identify the two TECC wires. The trials were made with all process parameters being optimized for the SiBiAg solder alloy at a very low process temperature of <150°C. Machine cycle time was at approx. 3600 solar cells/hour.

The results are very promising, too. Without any machine adjustment the TECC wires could be processed, and the adhesion force to Ag busbar was sufficient for both TECC-Wire and SiBiAg solder coated wires. However, a clear advantage of TECC-Wire over soldering could be observed immediately: TECC wires can be applied to any surface. We found very good adhesion of the TECC wires also to the aluminum on the rear side of the solar cell. However, reliability tests still need to be carried out. These first trials demonstrate the great potential for the usage of existing commercial stringers – of course with some modifications which will be required for mass production

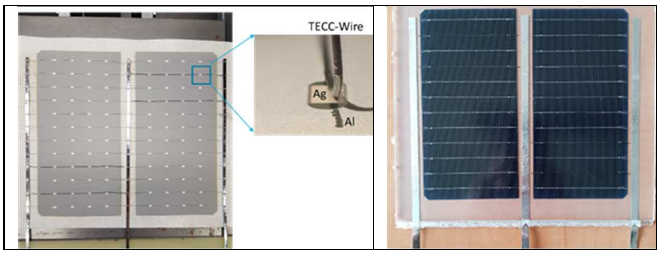


Figure 10: PERC solar cells connected with TECC wires and low-temperature solder wires with an industrial multi-wire stringer. The left image shows the rear side of the PERC solar cell and on the right side the front view after encapsulation of this small module

VII. CONCLUSION

We are presenting a new low-temperature interconnection technology for solar cells. TECC-Wire is an improvement of the modern multi-wire approach – basically a combination of multi-wire with using electrically conductive adhesives. This technology has been developed for the next-generation solar cells such as SHJ (silicon heterojunction) and c-Si/perovskite tandem which require a gentle and low temperature interconnection technology. The TECC-Wire technology is a new alternative approach besides using ECA and low-temperature soldering for the interconnection of temperature-sensitive solar cells. The advantages of the new technology are its low process temperature, the multi-wire approach, mechanical and electrical connection over the entire joint area, and the wires can be directly applied to TCO – conceptually no metallization required.

We have demonstrated the proof-of-concept which has been achieved successfully with PERC 9BB half-cut solar cells. We have achieved almost similar results compared to the soldered solar cells. In initial TC testing we find some early degradation in the first 100 cycles which may be attributed to the manual and thus inconsistent application of the TECC wires. After the first degradation all samples are stable up to TC 600 cycles.

The solar cells contacted with the newly developed semi-automated stringing machine show very low degradation after the first TC100 result. This confirms the assumption that fully manually made coupons were damaged during the TECC-Wire application process.

A first test run with an industrial multi-wire stringer showed comparable results to the standard wire coated with SiBiAg low temperature solder alloy in terms of adhesion, processability and electrical contacts by EL image characteristics.

One great advantage of the technology is that the thermoplastic glue sticks to entire solar cell surface and ensures the mechanical bonding and the electrical connection to basically any surface. Although nothing has yet been optimized, we could show that TECC-Wire technology can be basically applied to any kind of solar cell and any type of surface. Subject to necessary further reliability tests there is no large barrier for the implementation into industrial module manufacturing.

VIII. OUTLOOK

This new technology applies the advantages of multi-wire interconnection technology to temperature-sensitive solar cell architectures such as SHJ and c-Si/perovskite tandems. The TECC wires can even be directly applied to TCO, enabling the vision of metallization-free solar cells. Figure 11 is showing a 1-cell coupon contacted with TECC wires attached to a TCO surface without any metallization. This coupon is made from 100% silver- and metallization-free solar cell. The solar cell is contacted with 22 TECC wires. Because of its dark color the wires are not visible on the solar cell which makes it perfect for producing aesthetically pleasing full-black modules. Due to the low lateral conductivity of the TCO (which was optimized for printing a front grid) the FF of this sample was low at approximately 45% – but this demonstrates the vision of metallization-free solar cells.

The technology needs further optimization and investigation, but it has a great potential to optimize the interconnection of solar cells in terms of gentle low-temperature processing, mechanical bonding, and optimized output power.

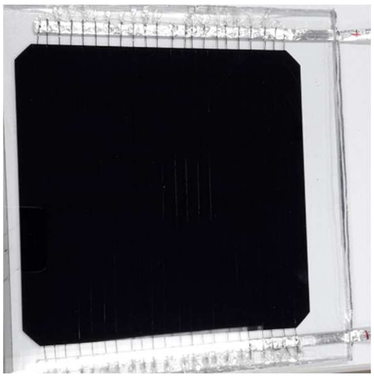


Figure 11: A metallization-free solar cell contacted with TECC-Wire technology. The wires are applied direct on the TCO layer and then the cells are encapsulated to glass/glass coupon using industrial standard laminator.

ACKNOWLEDGMENT

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