



Article

Stress and Fracture of Crystalline Silicon Solar Cell Interconnection Using Electrically Conductive Adhesive with Composite Metal Fillers for More Reliable Next Generation PV System Design

Sasi Kumar Tippabhotla ¹, Jeck Chuang Tan ¹, Darren Thomas ², Fitya S. Mozar ³ and Arief S. Budiman ^{1,2,4,5,*}

¹ Department of Engineering Product Development (EPD), Singapore University of Technology & Design (SUTD), Singapore 487372, Singapore; jeckchuang@hotmail.com (J.C.T.)

² Department of Manufacturing and Mechanical Engineering and Technology (MMET), Oregon Institute of Technology, Klamath Falls, OR 97601, USA

³ Bioinformatics and Data Science Research Center, Bina Nusantara University, Jakarta 11480, Indonesia

⁴ Industrial Engineering Department, BINUS Graduate Program-Master of Industrial Engineering, Bina Nusantara University, Jakarta 11480, Indonesia

⁵ Oregon Renewable Energy Center (OREC), Oregon Institute of Technology, Klamath Falls, OR 97601, USA

* Correspondence: suriadi@alumni.stanford.edu

Abstract

Conventional soldered interconnects—necessarily requiring high-temperature processes to melt solder (tin)—are posing reliability challenges to crystalline silicon solar cell modules due to residual stress stemming from the mismatch of the coefficient of thermal expansion of the materials involved. On the other hand, electrically conductive adhesives (ECAs) have been shown to exhibit sufficiently promising improvements in mechanical and electrical properties to be used as silicon solar cell interconnects. However, the current ECA technology is dominated by ECAs with dispersed silver particles, which makes them costly and could cause embrittlement of the ECA at higher concentrations. This study investigates the potential application of a novel ECA, with composite metal particles, made of a nickel and Sn95Ag4Cu1 solder mixture and dispersed in a high-density polyethylene matrix for the solar cell interconnection. The test PV modules show comparable electrical and mechanical performance to that of soldered cell modules, despite the fact that the ECA application is still rather early in its learning curve. The present study suggests that the novel ECA could lead to a promising alternative to the conventional soldering process and the more costly silver-filled ECAs.

Keywords: electrically conductive adhesive (ECA); solar cell interconnection; photovoltaics module; composite metal fillers; shingled solar cells

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1. Introduction

1.1. Why Conventional Solder Joints May Not Be Sustainable in Next-Generation PV Technologies

In crystalline silicon (c-Si) photovoltaic (PV) modules, the solar cells are electrically interconnected through solder-coated copper (Cu) interconnects (or ribbons) by a high-temperature (melting point of solder, ~220 °C) soldering process [1]. A schematic of a

typical solar cell string with soldered Cu interconnects is shown in Figure 1 below. Silicon is not a solderable material; hence, a thin silver busbar (created on the silicon cell by screen printing and baking at high temperature), as shown in Figure 1b, is used as a soldering contact. Upon cooling down from soldering temperature to room temperature (RT) of 25 °C, the soldered regions of the cell and the Cu interconnect (Figure 1b) develop residual thermal stresses due to the mismatch of the coefficients of thermal expansion (CTE) of Cu, solder and silicon [1–5]. These residual stresses often cause failures of the soldered metallic interconnects and fracture of silicon cells [1–6]. In addition to the residual stresses, the PV modules are subjected to thermal and mechanical loads during operation in the field, which could lead to further failures such as fatigue and creep in the metal interconnects [5–11]. The solder bonds between the solar cell and the Cu ribbons could also develop brittle intermetallic phases (especially in a very high-temperature climate, such as that of deserts), causing yet another mode of premature failures [12–15]. A review of PV module failures conducted by the International Energy Agency (IEA) revealed that 10% of failures are due to cell interconnects [16].

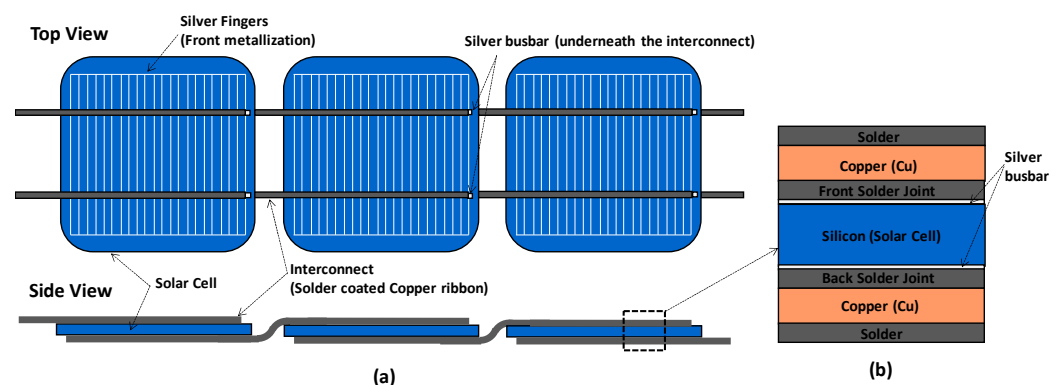


Figure 1. (a) Schematic of a typical string of interconnected solar cells; (b) detail of the solder joints between the solar cell and the solder-coated copper ribbons.

In the typical high-quality PV modules produced in high-volume manufacturing environments with tightly controlled processes, these residual stresses may be kept to the minimum and may not cause direct failures right after the solder process. However, our earlier investigations on encapsulated c-Si solar cells using synchrotron X-ray micro-diffraction (μ SXRD) revealed that the solder joints act as local stress concentrations, leading to higher residual stresses after the lamination process [17–22]. Due to recent technological improvements to reduce cost and increase power output and efficiency, silicon wafers are being made wider and thinner, which calls for thicker Cu ribbons to cope with the increased current [4], causing the CTE mismatch at the solder joint to become even more critical. Thicker ribbons create a higher rigidity of the interconnected structures, which could lead to higher stress and cracking during operation, and eventually pulling out the silicon wafer (electrically) from the PV module, causing permanent failure. Hence, it would be necessary to reduce the stress at the silicon solar cell interconnections. Specifically, to produce reliable solar photovoltaic modules with thin silicon technology, a low-stress interconnect technology needs to be developed [23].

1.2. Possible Path Forward

To address the high stress at the solder joints and the associated failures, researchers devised several innovative methodologies such as multi-wire interconnections, wave-shaped soft multi-wire interconnections, smart wire interconnection technology (SWCT) and interconnection by electrically conductive adhesives (ECAs).

In multi-wire interconnections [24–26], instead of a few (2 to 5) thick and wide Cu ribbons (as in the conventional method), many (12 to 20) thin and narrow Cu wires are used for interconnections and solder is used as the joining material. However, due to the increased compliance of the thin and narrow Cu wires, stress is expected to be reduced. The wave-shaped wire interconnection [27–30] technology is essentially a multi-wire technology and it provides additional stress relief due to the wave shape of the wires. This is a newly developed technology that is still under development and investigation. The multi-wire interconnects, although reducing the stress, may pose handling issues due to their low stiffness. Smart wire connection technology, SWCT [31,32], eliminates this issue by integrating the multi-wire interconnects into the encapsulant sheets, where the interconnection of the cells is incorporated into the lamination process by using a low-melting-point solder to comply with the maximum lamination temperature (~ 150 °C) [31]. This eliminates the need for a separate tabbing and stringing system to interconnect the cells. SWCT also gives increased module efficiencies due to the cylindrical shape of the wires, which reflect the incident light onto the surrounding cell regions [32]. In summary, multi-wire interconnections offer lower residual stress and deformation of the interconnected cells. However, they still use solder as the connecting material, and hence still have fatigue and creep failures upon thermal cycling and may contain brittle intermetallic phases, as explained earlier. In addition to SWCT, other multi-wire technologies also pose handling issues due to the flexibility of the wires. They may also call for production line modifications in high-throughput manufacturing.

Electrically conductive adhesives (ECAs) are a class of polymeric composites with micro- to nano-sized conductive particles dispersed in a polymeric resin, mainly developed for printed electronic gadgets that need flexibility [33,34]. The conductive particles are made of either metals or highly conductive non-metallic materials such as graphene and carbon nanotubes (CNTs) [33]. ECAs have been pursued for a long time (as early as 2002) for solar cell interconnections [34]. ECAs, being polymers with dispersed conductive (mostly silver) flakes/particles, offer high flexibility and low stress compared to conventional solders [4,34–38]. ECAs have also been proven to be better interconnection technologies for PV modules with shingled silicon solar cells [39,40] and metal wrap through (MWT) cells [41]. Recently, ECAs showed promising results for interconnection of thinner (thickness ~ 0.05 mm) c-Si cells, which are more fragile than conventional c-Si cells (thickness ~ 0.18 mm) and susceptible to breakage under the conventional soldering process [42,43]. In summary, ECAs offer lower residual stress and deformation of interconnected silicon cells of different types and thickness. However, ECAs degrade faster when subjected to aging and thermal cycling due to oxidation and breakage of metal polymer bonds [34–36,43]. Further, the electrical conductivity of ECAs is highly dependent on the weight fraction of the silver particles and, contrarily, the joint strength drops drastically with the increase in the silver fraction due to increased brittleness [36,38,44]. The cost of ECAs is also governed by the silver content. The cost can be controlled by reducing the silver and adding some other base metal to compensate for the loss of conductivity [44]. A low-cost ECA with CNTs was also tested for solar cell interconnection, which showed lower average conductance but gave positive hope for future improvements [45].

The review of low-stress interconnection technologies presented above shows that ECAs are a better option compared to multi-wire interconnections due to the following advantages:

1. ECAs are promising candidates for much lower thermal stress as they are very soft compared to solder, which is the bonding material in multi-wire interconnections.
2. ECAs can be used to interconnect advanced cell types such as shingles, MWT cells and very thin wafer (~ 0.05 mm thick) silicon cells. Multi-wire interconnections may not be suitable in such cases.

3. Engineering ECAs to have good conductivity, low silver content and high compatibility with the PV lamination process and operation will make them suitable for interconnection of next-generation highly reliable thin silicon PV technologies.

In this manuscript we present a novel 3D-printable ECA material with high-density polyethylene (HDPE) matrix and composite metal (a mixture of nickel and Sn95Ag4Cu1 solder) fillers, for interconnection of c-Si solar cells [46]. We present a methodology to interconnect the cells using this novel ECA and show the current–voltage (IV) characteristics and fill factor (FF) of the one-cell sample modules made of cells interconnected by this technology, in comparison to the control (solder) method. We further demonstrate the superior strength of the interconnections compared to that of solder joints by four-point bend testing and electroluminescence (EL) imaging. We also show some initial results of shingled cell interconnections achieved using this novel ECA.

2. Materials and Methods

2.1. Electrically Conductive Adhesive (ECA)

High-density polyethylene (Sigma Aldrich, Burlington, MA, USA) pellets, dried in an oven at 60 °C for 48 h before use, were taken for the matrix. The metal-filled composite with HDPE was prepared by the melt mixing process. The HDPE (melt index 12 g/10 min (190 °C/2.16 kg), Sigma Aldrich, Sofia, Bulgaria), nickel powder (3–7 µm, Stream) and low-melting-point metal (LMPM) alloy, Sn95Ag4Cu1, were melt mixed in a single-screw extruder. The volume proportion of nickel (Ni) particles to tin (Sn) alloy was 2:3 and the total composite metal (mixture of Ni and Sn95Ag4Cu1) loading by volume was 35% for this case. Composites with a different vol. % of the composite can also be prepared [46]. The temperature of the rotor for HDPE mixing was set to 220 °C, and the header was set to 220 °C. The speed of the extruder rotor was set to 50 RPM. A 1.75 mm diameter header die was used to extrude filaments, which were collected on a conveyor belt system moving at 0.5 mm/s. The filaments were cooled while moving on the conveyor belt by a 12 V electric fan of size 120 mm × 120 mm. No premixing of the components was performed. The fillets were collected and repalletized and melt extruded again to ensure homogeneous mixing. This process was repeated 3 times to obtain final filaments with a homogeneous composite. The diameters of the conductive filaments extruded were measured to be 1.75 ± 0.08 mm using a digital Vernier caliper and were directly used for 3D printing. A more detailed description of the composite preparation process and morphological investigation (SEM and EDX) can be found in the earlier report [46].

Although this composite consists of silver, its volume is ~0.84% only (for the 35% vol. metal loading case), which amounts to approximately 1.8% by weight. Hence, this ECA will be highly cost effective compared to commercially available ECAs with high silver loading [35,38]. The electrical conductance of the ECA with 35% volume metal loading is 23,000 S/m, evaluated at room temperature (25 °C), before heat treatment.

2.2. Solar Cell Interconnection and Module Lamination

The ECA described above can be 3D printed into any shape. For this study, we 3D printed thin strips of this ECA with a rectangular cross-section (width 1.8 mm, thickness 0.4 mm and length 150 mm), as shown in Figure 2a, to facilitate the manual assembly for solar cell interconnection. Single-cell PV modules, with ECA interconnects, were made by manual processing in the laboratory. The conventional solder-coated copper (Cu) ribbons were used for interconnection. The ECA strips were placed between the silver busbars of the cell and the Cu ribbons, as shown by the schematic in Figure 2b. The Cu ribbons and ECA strips are held in place on the cell by a commercially available 3M Scotch Tape of

thickness 0.04 mm, as shown in Figure 2c,d. Figure 2e shows a closeup view of the Cu ribbon and ECA strip on the cell's busbar.

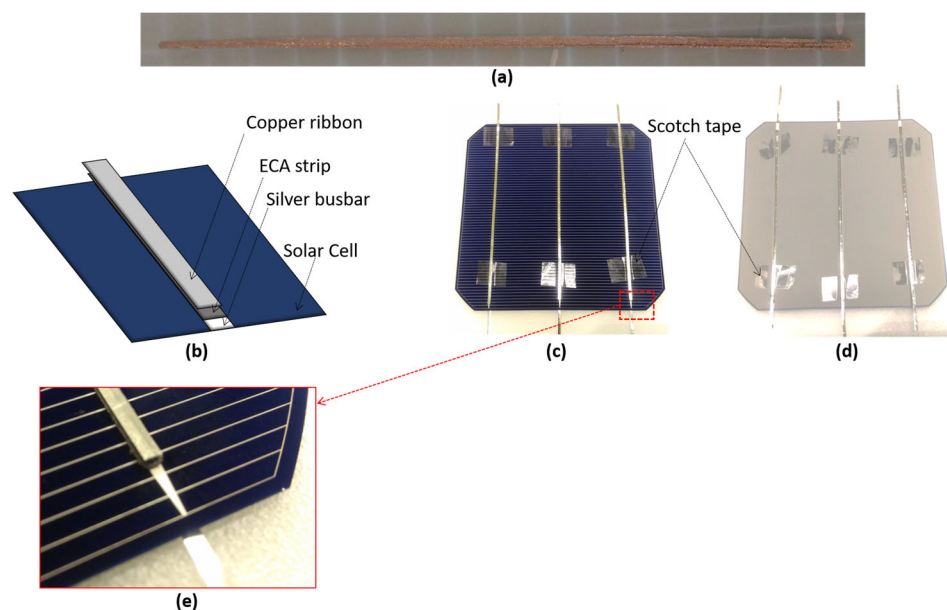


Figure 2. (a) 3D-printed ECA strip of rectangular cross-section, dimensions: length 150 mm, width 1.8 mm, and thickness 0.4 mm; (b) schematic lay-up of the cell interconnection with ECA; (c) front-side, and (d) back-side lay-up of the cell interconnection with ECA; (e) detail view showing lay-up of silver busbar of the cell, ECA strip, and Cu ribbon. Note that the ECA strip and the Cu ribbon are held in place by a commercially available 3M Scotch Tape of 40 μm thickness, as shown.

The cells with the interconnects were then placed between two layers of encapsulation (lamination) polymer, EVA, and a tempered front glass, and laminated on a flatbed laminator, as shown in Figure 3a. Three single-cell module samples, E1, E2 and E3, were made with an EVA interconnection. One of the finished test modules is shown in Figure 3b. Three control samples, S1, S2 and S3, were also made with standard machine soldered cells for comparison. The lamination parameters used for making the samples are shown in Table 1 below.

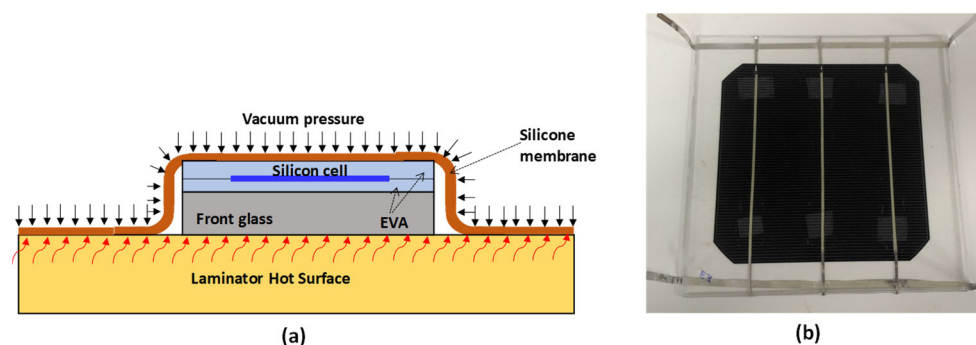


Figure 3. (a) Schematic of PV module lamination process; (b) picture of sample single-cell module with ECA interconnection.

Table 1. Lamination parameters.

Lamination Parameters		
Sample	E1, S1	E2, E3, S2, S3
Temperature	150 °C	160 °C
Vacuum Pressure	0.1 MPa	0.1 MPa
Vacuum Delay	45 s	45 s
Vacuum Time	2 min	2 min
Heating Time	10 min	10 min
Total Lamination Time	12 min 45 s	12 min 45 s
Cooling to Room Temperature	No control, Allowed to cooldown to the room temperature in the laboratory air	

As shown in Table 1, samples E1 and S1 were laminated at 150 °C and the rest were laminated at 160 °C. The vacuum pressure applied during lamination removes air trapped between different layers of the laminate and helps to achieve good adhesion of the encapsulant (EVA) with the front glass and the silicon cell. In the case of samples with an ECA, vacuum pressure also helps to form good adhesion of the ECA with the cell and the Cu ribbons.

The manual method of assembling the cells with ECA and Cu ribbons described above was used to make the sample PV modules for different testing purposes. In order to use the ECA in the real solar PV module fabrication process, the method needs to be mechanized and readily applicable to high-throughput manufacturing. The conventional soldering method shown in Figure 4a is well established, especially for standard-thickness (~0.18 mm) c-Si cells [42]. However, it requires preheating of the cells and heating of the cells and Cu ribbons to the soldering temperature (>200 °C), which leads to high thermal residual stresses. Additionally, the long string of cells (12 cells) made by this method for a standard full-size PV module may cause breakage of cells during handling before lamination. In the case of thin c-Si wafer cells, the cell breakage rate goes up because the cells are more fragile. We propose the scheme shown in Figure 4b to make interconnections of solar cells with the ECA in an automated factory environment. The Cu ribbons will be pre-coated with the ECA layer as shown (Figure 4b). Alternatively, the Cu ribbons with ECA layers can also be 3D printed directly [46]. These Cu ribbons can then be laid-up on the cells in the required order, along with the other lamination materials, as shown in Figure 4b, by pick and place robots. The lay-up can then be transported to the lamination process.

This method of interconnection process completely removes the tabbing/stringing process and requirement of a high-temperature heating process for soldering. The 3-step fabrication process (Figure 4a) can be modified to a 2-step process (Figure 4b) using the ECA interconnections. Hence, the cell breakage due to soldering-induced thermal residual stresses and handling of long cell strings can be eliminated. This will lead to a high-yielding module fabrication process that is especially suitable for processing of PV modules with thin c-Si wafer solar cells. The lay-up process can also be further simplified by integrating the Cu ribbons with ECA strips into the encapsulation polymer sheets, similar to the SWCT technology [31,32].

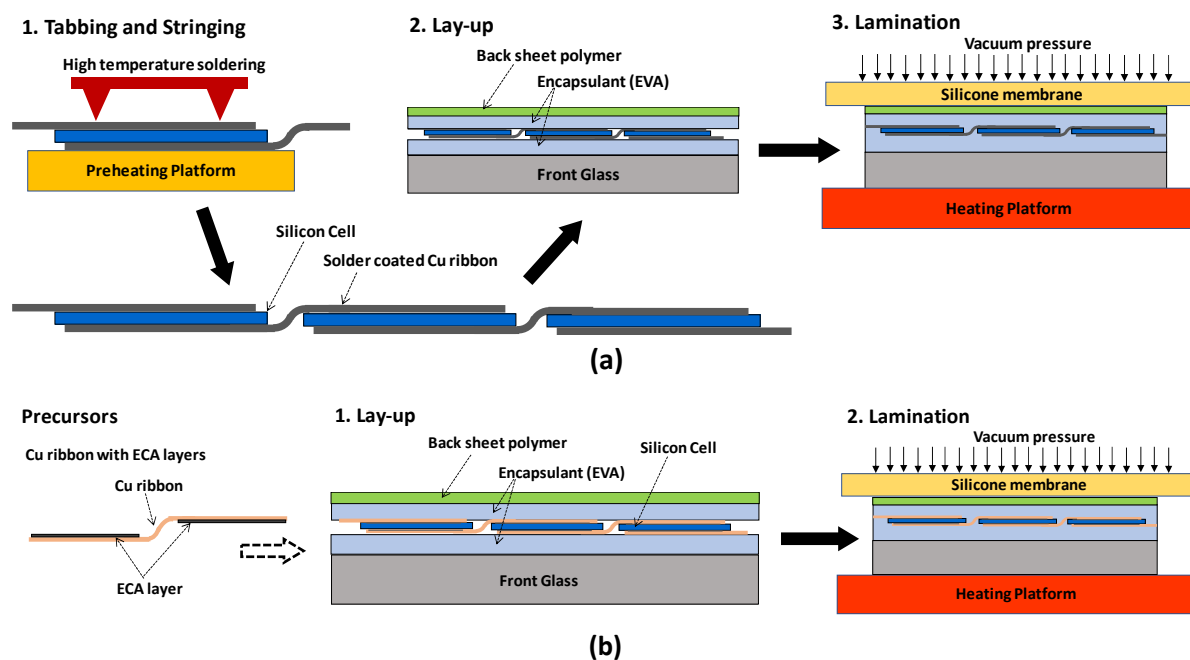


Figure 4. Schematic of PV module fabrication process with: (a) conventional soldering, (b) ECA interconnection. The precursor step is the pre-fabrication step in (b) equivalent to the Tabbing and Stringing step in the conventional soldering method (a) and hence the dashed arrow (not solid) shown in (b)—as it is not formally part of the ECA interconnection method.

2.3. Characterization and Performance Evaluation

The single-cell PV module samples described in Section 2.2 were subjected to flash testing [47] on a “Pasan SunSim 3B” sun simulator at the Solar Energy Research Institute of Singapore (SERIS) [48] to evaluate the electrical performance based on the current–voltage (IV) characteristics.

These test modules were later subjected to electroluminescence (EL) testing [49] to evaluate the cell cracks before mechanical testing. Mechanical loading was applied by a 4-point bending setup on an Instron 5982 mechanical tester, as shown in Figure 5, to evaluate the load carrying capacity of the c-Si cells before fracture. Subsequently, EL testing was again conducted to evaluate the cracks in the cells after the mechanical loading. The results of the characterization are discussed in Section 4.

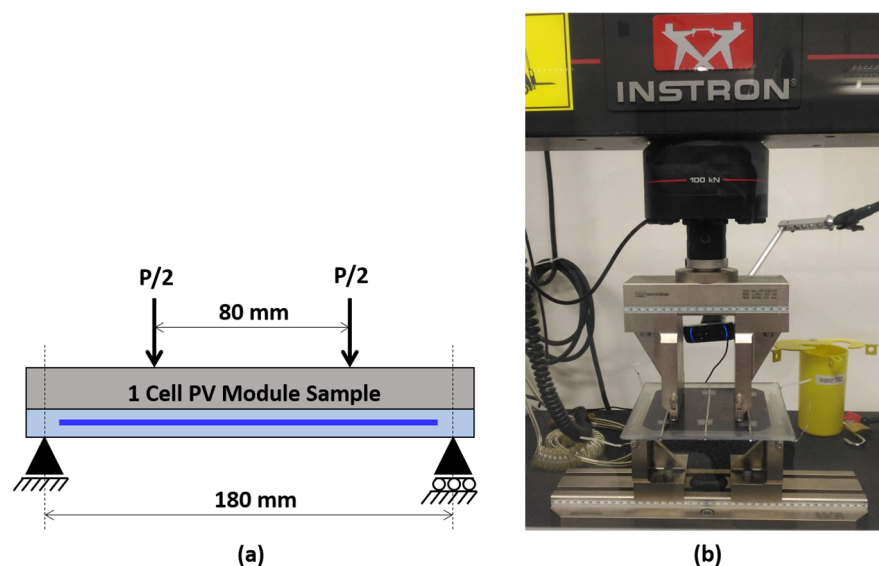


Figure 5. (a) Schematic and (b) actual picture of the 4-point bending test of 1-cell PV module sample on Instron 5982 mechanical tester.

2.4. Finite Element Modeling

The single-cell PV module samples described in Section 2.2 are subject to the limitations of manual processing, such as thicker ECA filaments and manual lay-up of the laminate components, which may introduce failure modes that are not the actual characteristics of the ECA. Hence, we supplemented the actual test modules with simulation of the soldering and ECA interconnections using finite element (FE) simulations. A simple generalized plane strain FE model was set up for this purpose, as shown in Figure 6 below.

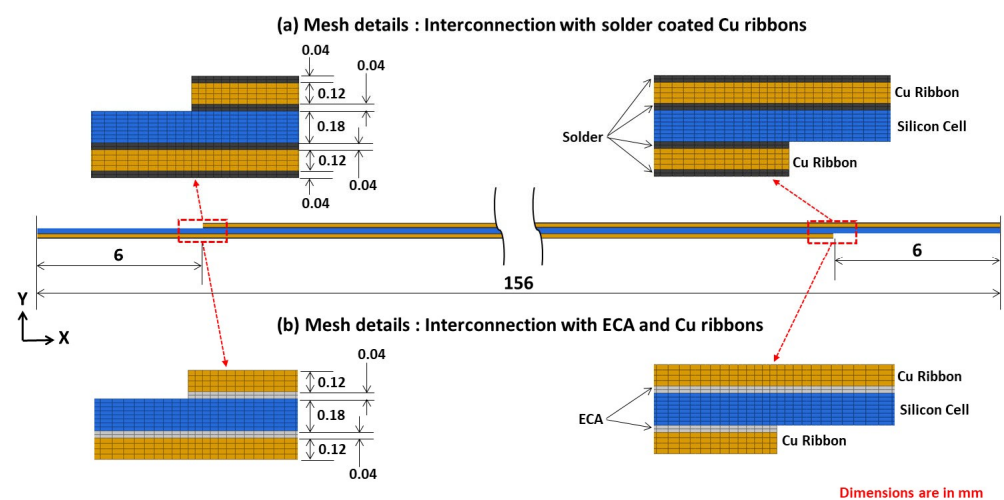


Figure 6. Details of the finite element model for (a) conventional soldering and (b) ECA interconnection. This FE model is a plane strain representation of the interconnection along the Cu ribbon (ref. Figure 1) for a single cell.

As shown in Figure 6, this FE model is a plane strain representation of the interconnection along the Cu ribbon (ref. Figure 1) for a single cell. The model is essentially the same for both cases, with the differences identified in the mesh details shown separately for the soldered case (Figure 6a) and ECA case (Figure 6b). In both cases, the Cu ribbon on the top of the cell is bonded 6 mm from the left edge of the cell. Similarly, the bottom Cu ribbon is bonded 6 mm from the right edge of the cell. This is to avoid the possibility of shorting of the Cu ribbons from the top and bottom of the cells. Further, this will also help to avoid edge breakage of the cells. However, due to this, the interconnection at the edges of the cells is no longer symmetric, hence leading to warpage and high bending stress in the cells. We selected this model to demonstrate the effectiveness of the ECA in reducing the cell stress and warpage upon interconnection. The temperature-varying elastic (storage) modulus of the ECA, as shown in Figure 7, along with the loss modulus and $\tan(\delta)$, were determined from the dynamic mechanical analysis (DMA) at a 1 Hz frequency [50]. The test sample was held in film tension mode in the DMA and it failed beyond 110 °C due to softening of the HDPE. The Poisson ratio of the ECA was 0.4. Further, the coefficient of thermal expansion (CTE) of the ECA was estimated to be 99.4 $\mu\text{m/m/}^\circ\text{C}$, based on the volume fractions of the constituents (HDPE, Ni and Sn95Ag4Cu1 solder), using a simple rule of mixtures. The properties of the rest of the materials are as specified in our earlier report [20]. Note that the silicon was assumed to be isotropic for this simple simulation. The Cu ribbon was elastic plastic and the rest of the materials were assumed to be linearly elastic. Steady-state FE analysis of the interconnection process was carried out to simulate the cooldown from 210 °C to room temperature in the case of the soldered

interconnection. In the case of the ECA interconnection, the cooldown from 160 °C to room temperature was simulated under steady-state conditions. The results are shown in the following section. In both models, nodes on the vertical line passing through the center of the model are fixed in the horizontal direction and one node at the intersection of the vertical and horizontal centerlines of the cell is fixed in all directions to avoid rigid body motion.

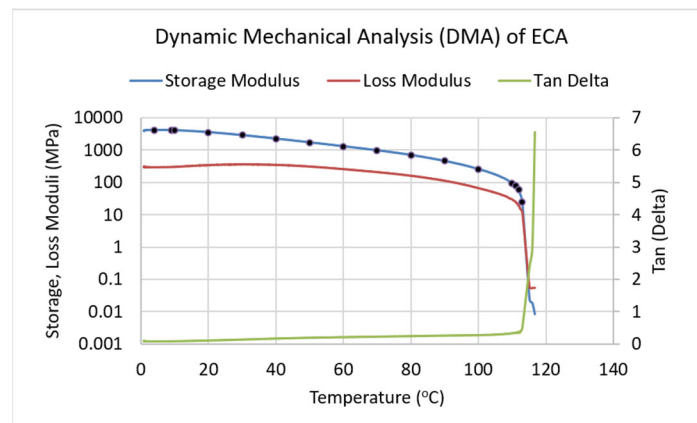


Figure 7. Elastic (storage), loss moduli and $\tan(\delta)$ of the ECA as a function of temperature, determined by dynamic mechanical analysis (DMA). The points denoted are used for elastic modulus of ECA in FEA simulations.

3. Results and Discussion

3.1. Electrical Performance

The current–voltage (IV) characteristics of the test PV samples from the flash test are shown in Figure 8 below. Figure 8a–c show the IV and power curves for soldered samples S1, S2 and S3, respectively. Figure 8d–f show the same for ECA samples E1, E2 and E3. All the curves are closely comparable to each other, except those of E1 (Figure 8d). This is because the ECA softens around 120 °C, but higher temperatures will help achieve good adhesive bonding with the interfacing surfaces of the silicon cell and the Cu ribbon. The samples S1 and E1 are laminated at 150 °C, which is not sufficient for good bonding of the ECA with the other interfaces, leading to high resistance, whereas the other samples, laminated at 160 °C, show comparable performance to the soldered samples. Table 2 shows the salient electrical properties of the test modules, such as short circuit current (I_{sc}), open circuit voltage (V_{oc}), current at maximum power (I_{mp}), voltage at maximum power (V_{mp}), maximum power output (P_{max}) and fill factor (FF). As explained above, the fill factor of the sample E1 is very low compared to that of the other samples, and so are I_{mp} , V_{mp} and P_{max} .

Table 2. Salient electrical characteristics of test PV module samples.

Sample	Lamination Temperature (°C)	I_{sc} (A)	V_{oc} (V)	I_{mp} (A)	V_{mp} (V)	P_{max} (W)	FF
S1	150	8.6549	0.64069	7.918	0.5058	4.0048	72.22
E1	150	8.4827	0.63463	7.144	0.3723	2.6599	49.41
S2	160	8.602	0.63575	7.911	0.4999	3.9547	72.31
E2	160	8.4711	0.6349	7.857	0.4875	3.8301	71.21
S3	160	8.5787	0.63713	7.942	0.4855	3.8557	70.54
E3	160	8.4076	0.63423	7.794	0.4745	3.6982	69.35

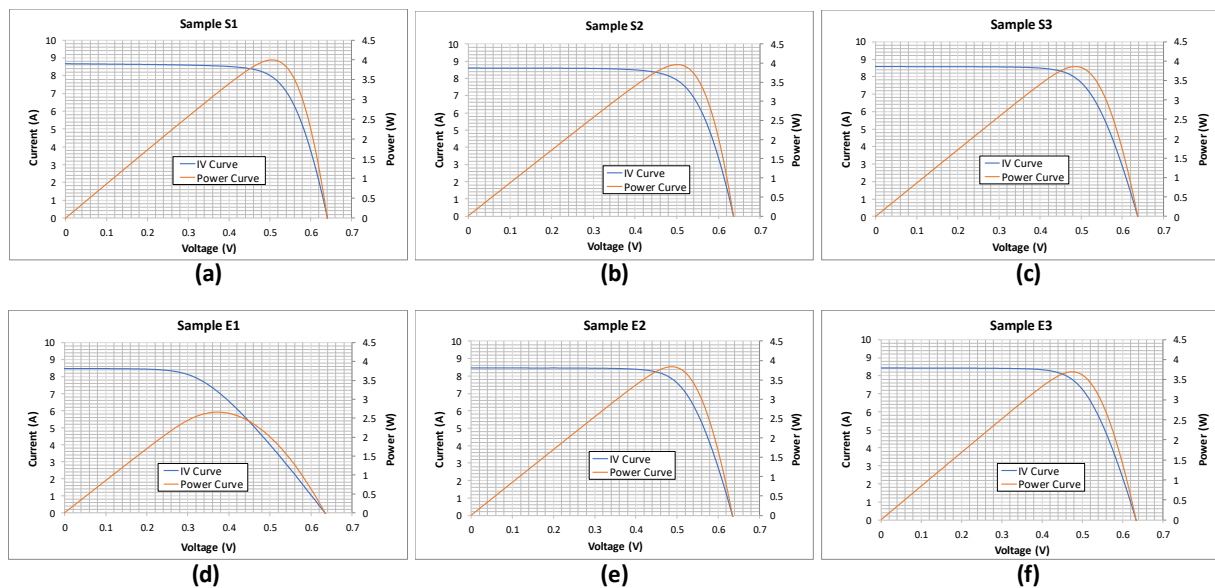


Figure 8. Current–voltage (IV) and power curves of test PV modules: (a) sample S1; (b) sample S2; (c) sample S3; (d) sample E1; (e) sample E2; (f) sample E3.

3.2. Mechanical Integrity

The mechanical integrity here is measured using the pull test of the overall laminate structure. We focus on how the overall laminate with ECA interconnections compares in terms of mechanical integrity to the standard laminate with standard soldered interconnects (as a control group). The mechanical integrity of the overall laminate structure here is manifested in the effects on the integrity of its most brittle components in the laminate structure, i.e., the thin and fragile silicon solar cells.

Figure 9 shows EL images of the sample PV modules before mechanical loading (four-point bending). It can be noticed that some of the samples have pre-cracks, as highlighted, originating from the soldering/lamination process. In the case of ECA modules E1 and E3, the cracks originate from the manual assembly process of ECA strips and Cu ribbons on silicon cells, due to the non-uniformity of the 3D-printed ECA strips. This is a limitation in our laboratory process; in actual high-volume production, ECAs can be deposited directly on the Cu ribbon to have well-controlled surface properties to avoid such failures. The dark color patches on the soldered samples S1 and S2 are due to the flux overflow of the automatic stringer. Figure 10 shows EL images of the sample PV modules after four-point bending testing to a 500 N load. The silicon cells in the samples S1, S2, E1 and E3 cracked under this load. The silicon cells in the soldered modules S1 and S2 developed cracks along the edge of the soldered Cu ribbon. This clearly indicates the effect of high residual stress and micro-cracking due to soldering [2,3]. It should also be noted that the pre-cracks in the cells of these modules did not propagate as they are slightly away from the solder joint (high-stress zone). The silicon cells in the ECA modules E1 and E3 failed due to propagation of the pre-cracks which were formed during the lamination process. As discussed before, these micro-cracks are the result of our 3D-printed ECA strips with local non-uniformity and manual processing of the module lay-up for lamination, which would not typically be issues in high-volume manufacturing environments. The samples S3 and E3 did not develop cell cracks under a 500 N load. It can be noticed from Figure 10 that the damage due to cell cracking may not be significant, as the dark regions in the EL images are confined to Cu ribbon lines and crack paths [51–53]. Figure 11 shows EL images of the samples after four-point bending to a 1000 N load. Silicon cells in all the samples cracked under this load.

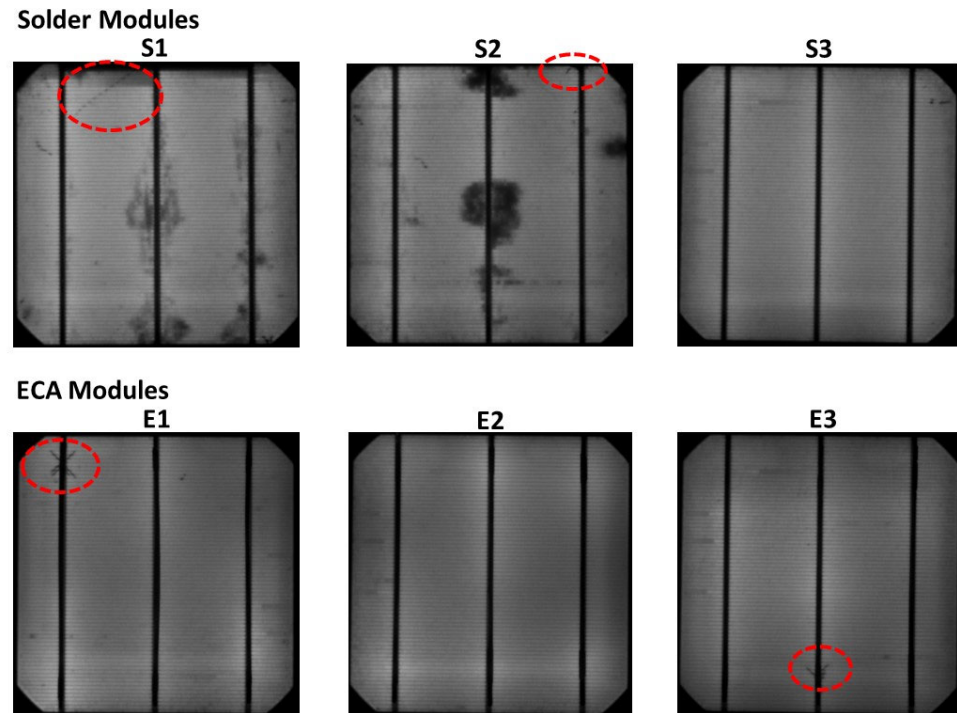


Figure 9. EL images of the test PV module samples before 4-point bend testing. The cracks in the cells (formed during soldering/lamination) are encircled by red-color dotted ovals.

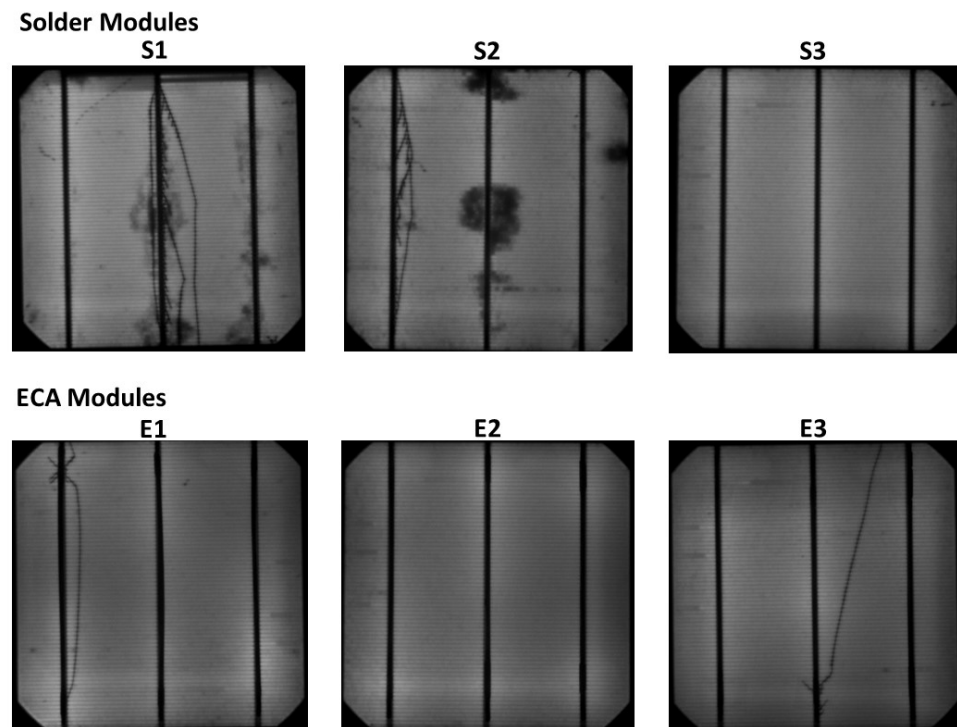


Figure 10. EL images of the test PV module samples after 4-point bend testing to 500 N.

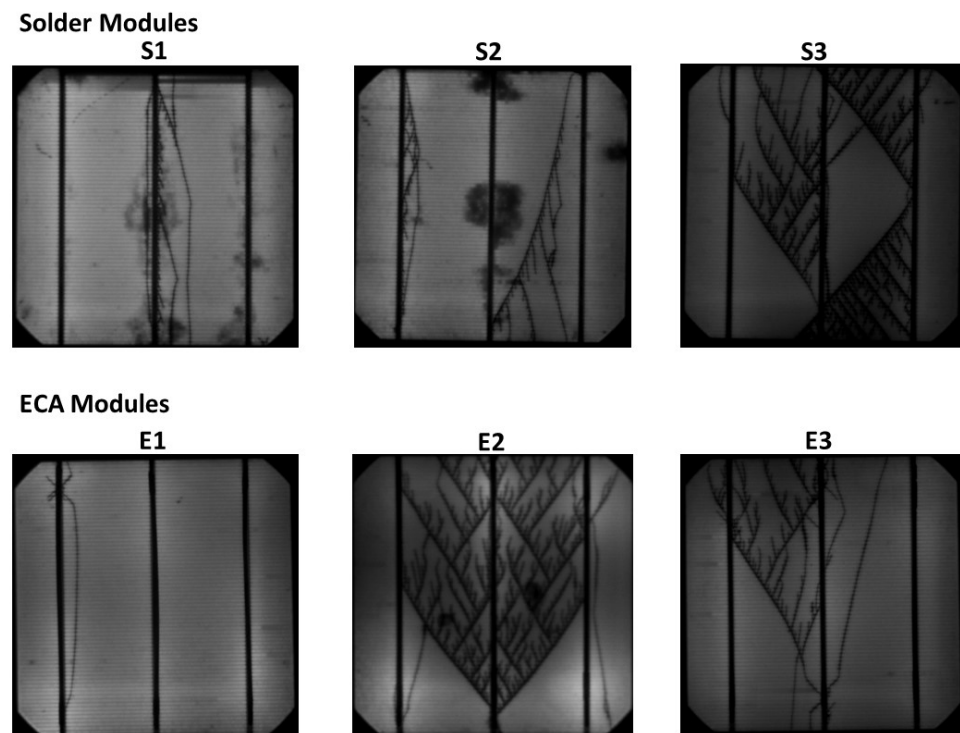


Figure 11. EL images of the test PV module samples after 4-point bend testing to 1000 N.

However, the silicon cells in the modules S3 and E2, which did not crack under a 500 N load, fractured catastrophically under a 1000 N load, typical of monocrystalline silicon, which is a brittle material. Interestingly, the cells in the modules S1 and E1, which cracked under 500 N (due to pre-cracks from soldering/lamination), did not crack further. This may be because of the stress relief (or dissipation of elastic strain energy) due to the propagation of the pre-cracks. The cells in the samples S2 and E3, which cracked under a 500 N load, further cracked, but not catastrophically. The cell cracking in these two cases is again a result of the propagation of pre-cracks (ref. Figure 9). The actual load at which the cells cracked is shown in Table 3 below. It shows the load at which the “first crack” in the cell formed (or the pre-crack propagated) and the final failure of the cell (ultimate fracture). The cells in the modules S1 and E1 did not crack further under a 1000 N load; hence, the load at ultimate fracture is >1000 N.

Table 3. Fracture load capacity of the silicon cells in the test PV modules, under 4-point bend testing.

Sample	Load at Silicon Cell Fracture (N)	
	First Crack	Ultimate Fracture
S1	375	>1000
S2	400	510
S3	850	850
E1	210	>1000
E2	770	770
E3	150	800

From the cell fracture load at “first crack” in Table 3, the ECA modules appear to be of lower strength. However, given the effect of the pre-cracks, which readily propagated at low loads in the ECA modules, one needs to consider the load to “ultimate fracture” to assess the fracture strength of the modules. From this, we can see that the ECA modules show comparable strength to the soldered modules. Another important parameter which needs to be considered in the strength evaluation is the bending of the cells during the

lamination process, which induces high stress in the cells. Figure 12 shows the local region around the cell and Cu ribbon solder/ECA joint during the lamination process. Under the action of vacuum pressure (0.1 MPa), the cell bends about the edge of the Cu ribbon. In the case of the soldered modules, as shown in Figure 12a, the cell bends about the Cu ribbon (thickness 0.18 mm). However, in the case of the ECA modules, the bends occur about the stack of the Cu ribbon and ECA strip (total thickness 0.58 mm), as shown in Figure 12b. Hence, the ECA modules cause greater cell bending than the soldered modules, as shown by the “dotted red lines” in Figure 12a,b. This means the ECA modules are subjected to higher cell bending stress during lamination and, even then, they show comparable strength to that of the soldered cell modules. The higher bending stress is a result of the thicker ECA strip, which is a limitation due to our manual handling of the components for the module lay-up. The ECA thickness can be reduced in the actual process by integrating it with the Cu ribbon, as explained earlier. That would eliminate the higher bending stresses in the cells, and the ECA modules are expected to show higher strength compared to the soldered cell modules. Further, the reduction in the ECA thickness helps to reduce the resistance of the interconnection (as the resistance is inversely proportional to the cross-sectional area). Hence, it is expected to improve the fill factor and the maximum power output as well.

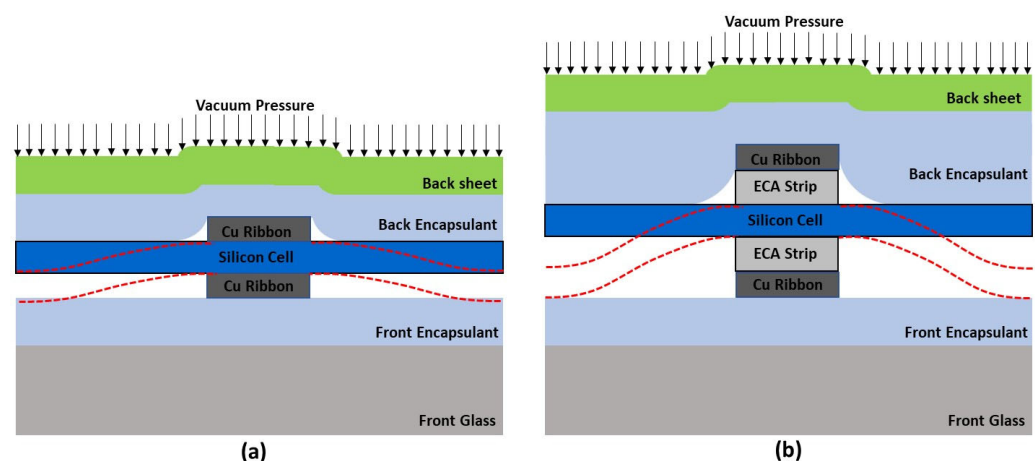


Figure 12. Schematic of bending of the silicon cell about the Cu ribbon, under vacuum pressure (0.1 MPa), during the PV module lamination process for (a) soldered silicon cell and (b) ECA interconnection. The red-color dotted lines indicate the bent shape of the cell, showing higher bending of the cell in the case of ECA interconnection. Note that the thicker ECA strip is a limitation in our laboratory process due to manual assembly. In the actual mechanized production, the ECA thickness can be reduced and higher bending stress in the cell can be eliminated.

3.3. Stress Simulation

Further, the bending stress in the cell during the lamination process can be eliminated by integrating the ECA-coated Cu ribbon into the encapsulation sheet, as shown in Figure 13 below. This concept is similar to the SWCT technology discussed before [31,32], which has been proven to work; our ECA can be made compatible with this technology [46]. This could be a way to eliminate the residual stresses in the case of thin silicon wafer cells, which are more fragile and prone to breakage [3,42].

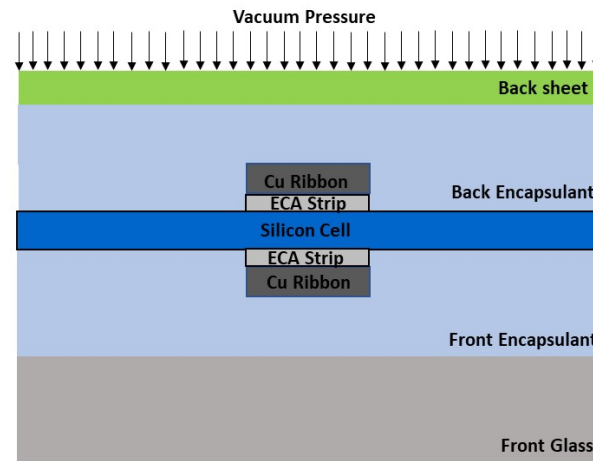
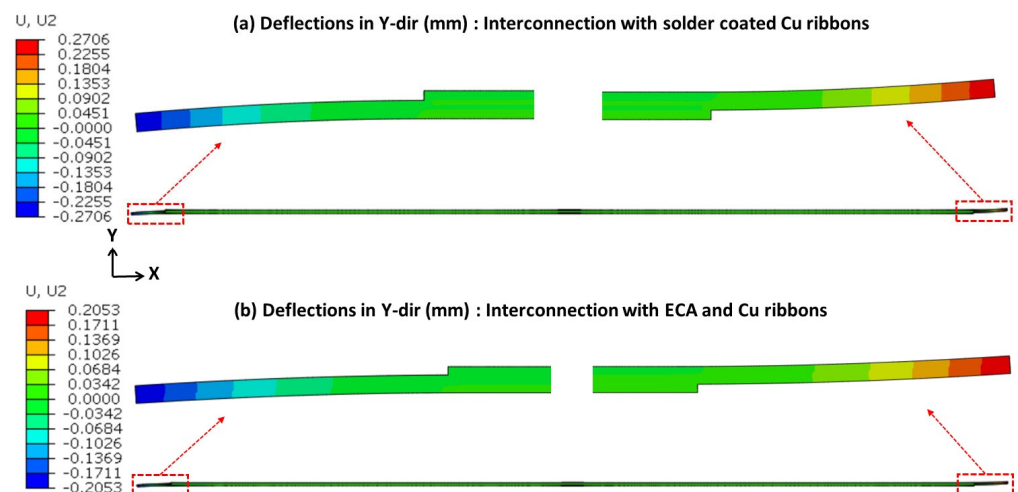


Figure 13. Schematic of the silicon cell lamination with encapsulation sheets embedded with ECA-coated Cu ribbons. Bending of the silicon cell under vacuum pressure (0.1 MPa) is eliminated in this case.

From the module testing results, although the ECA modules show comparable performance to the soldered ones, they are subjected to manual processing limitations. So, we used finite element simulations to reinforce the effectiveness of the ECA for the interconnection. Figure 14 below shows deflections and stresses from the FE simulations for both cases. It is clear from Figure 14a,b that the ECA interconnection reduces the warpage of the cell at the edges, which leads to lower damage during the lamination process. The stress plots in Figure 14c,d clearly show that the bending stress in the silicon cell reduces from 460 MPa to 209 MPa, which is a huge reduction (~54%). It should be noted that the warpage (Figure 14b) and stress (Figure 14d) simulated in the case of the ECA interconnection is for demonstration of its effectiveness only. Because the ECA interconnection process is integrated with the lamination process, the actual warpage of the cell will be much lower, and therefore the bending stress will also be considerably lower.



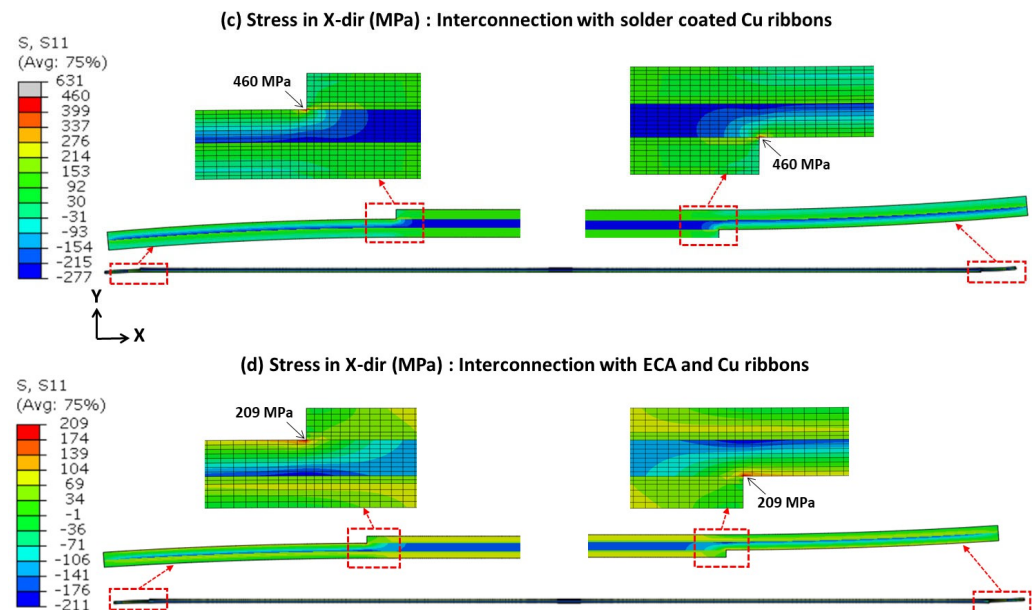


Figure 14. Deflections and stress near the edges of the silicon cell in soldered and ECA interconnection cases. Maximum bending stress in the cell is marked in the magnified plots of (c,d).

3.4. Further Potential Applications

The ECA-based cell interconnection helps to reduce the residual stress in the generic-design c-Si solar cells compared to the standard soldered interconnects. However, in the case of recent technologies such as shingled silicon cells, soldered interconnections may be ruled out due to high stresses and handling issues. ECA might be the only option in such a case [39]. Solar cell shingles are small pieces of silicon solar cells designed to eliminate the unproductive region (silver busbar) of the solar cell covered by the Cu interconnects. As shown in Figure 15a, the silver busbar at the back-side edge of a shingled cell is directly connected to the silver busbar on the front-side edge of the adjacent shingled cell by an overlapping adhesive joint (using an ECA). A schematic of a solar PV module with shingled silicon cells is shown in Figure 15b below. Currently, shingled silicon cells are not commercially available; hence, we cut a standard silicon cell into pieces to structurally resemble the shingles. A sample PV module with these shingle-like silicon cell pieces, with ECA interconnects, was made using the lamination process described in Section 2.2 (ref. Figure 4b). The front and back sides of the sample module with the shingle-like silicon cell pieces are shown in Figure 15c,d respectively. Figure 15e shows the EL image, indicating very good interconnection of shingle cells without cell cracks. This demonstrates the applicability of our ECA for interconnection for shingled silicon cells.

Our earlier study [20] shows that the high residual stresses in the interdigitated back-contact (IBC) c-Si solar cells is due to the warpage of the cells around the solder joint with the Cu interconnect induced by the CTE mismatch. Using the ECA for interconnection of these cells, the soldering process can be removed, and the cell interconnection can be integrated with the lamination process, similar to the process proposed in Figure 4b. In such a case, there will be no warpage of the cell around the interconnect joint. Hence, the high residual stress in the encapsulated IBC c-Si cells can be eliminated.

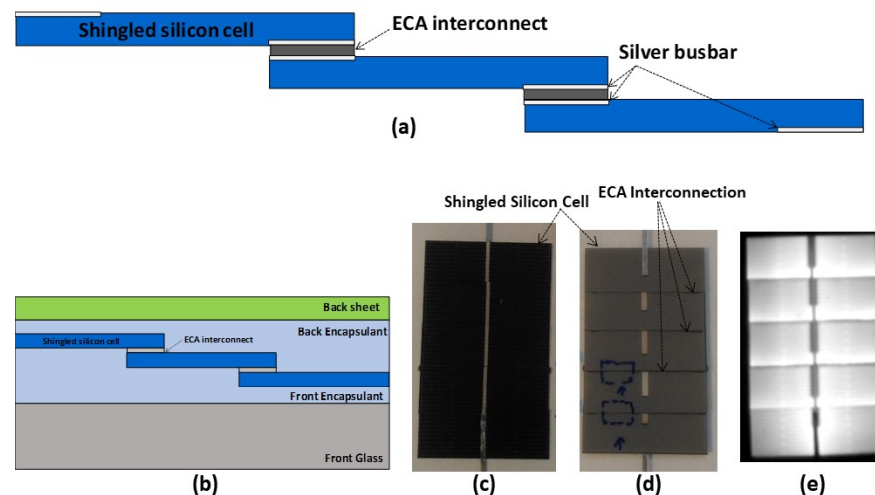


Figure 15. (a) Schematic of shingled cell interconnection with ECA; (b) schematic of the solar PV module with shingled silicon cells; (c) front side and (d) back side of sample PV module with shingle-like silicon cells connected by ECA; (e) EL image of the sample PV module with shingle-like silicon cells.

In summary, we demonstrated the use of an electrically conductive adhesive based on an HDPE matrix and nickel-and-tin-based conductive metal fillers (with minimal silver content) for interconnection of crystalline silicon solar cells in PV modules. The ECA was shown to form good bonding with the cells and Cu ribbons, giving a comparable fill factor to that of standard soldered modules. The fill factor of the ECA modules, laminated at 160 °C, is 0.7 to 3.3% less than the average fill factor of the soldered modules. The test PV modules, with an ECA interconnection, are limited by the 3D-printed ECA strip thickness and manual processing of the lamination lay-up. Due to this, they are subjected to higher cell-bending stress during lamination (ref. Figure 12). However, the test PV modules with an ECA show comparable strength to the soldered modules under a four-point bending test. Hence, they are expected to show higher strength in actual mechanized production processes, where the ECA thickness and module lay-up processes are well controlled. Lower warpage and stress of the cell, shown by FE simulations, in the case of ECA interconnection, confirm this (ref. Figure 14). The ECA can be coated or deposited onto the Cu ribbon in liquid form (when heated) or it can be 3D printed onto the Cu ribbon [46]. It can also be integrated into the encapsulation sheets, as shown in Figure 13, to reduce cell bending and simplify the process [31]. As shown in Figure 15, this ECA can also be used for interconnection of shingled solar cells without Cu ribbons. Further, the high residual stresses in the encapsulated IBC c-Si cells due to local warpage around the solder joint [20] can also be eliminated. The qualification of the ECA interconnects for long-term thermal and environmental reliability [50,54] will be a part of our further investigation, as well as its further implementation in potential emerging advanced solar photovoltaics and renewable energy systems [55–60].

4. Conclusions

Effective interconnection of c-Si solar cells using an electrically conductive adhesive (ECA) was demonstrated in the present study. Unlike most of the earlier reports, the ECA used in this investigation is not based on silver or carbon particles; it is prepared by dispersing composite metal (nickel and Sn95Ag4Cu1 solder) particles in an HDPE matrix, which can be 3D printed into any shape. Because of this, the novel method of interconnection of silicon solar cells with this ECA has been shown to allow several alternatives and the flexibility to integrate it with the lamination process, eliminating the need for

conventional separate tabbing and stringing processes. Further, the ECA strips have also been shown in the present study to allow easier integration with the encapsulation sheets to reduce the bending stress in the cells and make them applicable to the interconnection of extremely thin silicon wafer cells. One of the limitations of the present study is that the test PV samples prepared using this ECA are subject to defects and high bending stress during lamination due to the limitation of laboratory processing, but this can be eliminated in a real production process. Even with this limitation, the test PV modules with an ECA have showed comparable electrical and mechanical performances to those with standard automated soldering. FE simulations also have shown favorable results, with low warpage and cell stress for the ECA interconnections compared to soldered ones. Hence, the novel ECA interconnection methodology in the present study has shown a promising alternative for interconnection of both standard and thin c-Si cells, which can be readily integrated with mainstream production lines in global PV industries. Furthermore, we have also provided crucial experimental evidence that the ECA interconnection methodology may be further applied to reduce residual stresses in back-contact silicon cells and shingled cells in existing mainstream PV modules/products in the present market.

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