# A review of interconnection technologies for improved crystalline silicon solar cell photovoltaic module assembly

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**Abstract**

The identification, adoption and utilisation of reliable interconnection technology to assembly crystalline silicon solar cells in photovoltaic (PV) module are critical to ensure that the device performs continually up to 20 years of its design life span. With report that 40.7 % of this type of PV module fails at interconnection coupled with recent reports of increase in such failure in the tropics, the review of interconnection technologies employed in crystalline silicon solar cells manufacture has become imperative. Such review is capable of providing information that can improve the reliability of the system when adopted which in turn will increase silicon PV module production share more than the current value of 90.956%. This review presents the characteristics of interconnect contacts in conventional cells and other unconventional crystalline silicon cells. It compares series resistance, shadowing losses and the induced thermo-mechanical stress in the interconnection for each interconnection technique employed. The paper also reviews interconnection technologies in these assemblies and presents a comparison of their concept, cell type, joint type, manufacturing techniques and production status. Moreover, the study reviews and discusses the material and technological reliability challenges of silicon solar cells interconnection. The review identifies laser soldering technology as one which has the potential of making interconnection with higher reliability when compared with conventional soldering technology. It was found that this technology supports the current design trend of thinner, wider and cheaper crystalline silicon solar cells significantly whilst producing interconnection that experience relatively lower induced thermo-mechanical stress. The authors recommend that wider acceptance and usage of laser soldering technology could improve the performance and consequently extend the mean-time-to-failure (MTTF) of photovoltaic modules in general and particularly the ones which operates in the tropics.  This will enable improvement in the reliability of PV modules for sustainable energy generation.

***Keywords:*** *Photovoltaic modules; Crystalline silicon solar cells; Interconnection technology; Reliability*

## 1. Introduction

Photovoltaic (PV) modules constitute significant development in the worldwide green energy sector in the current campaign to increase sustainable energy production. Currently, the module is in huge demand because they are now used to supply electrical power [1, 2] to many applications. To meet the demand, the production of solar cells has increased because the modules are assembled by interconnecting solar cells to each other. It is expected that in the year 2020, the world annual production of solar cells will be around 100 $GW_p$ ($W_p$, is peak power produced under standard test conditions). While this amount of sustainable power production seems substantial, the continued operation of the module up to its design service life has become a concern because the desired power generation is lower than expected.

The silicon solar cells have been identified as the most viable option suitable for large volume production [3]. However, it has been reported that the continual generation of electricity by PV modules, manufactured using this type of cell, in the field for a minimum life span of 20 years has been a concern [1, 4-6]. One of the key challenges is untimely failure of solar cells interconnection in the modules [7]. The interconnections provide electrical, mechanical and thermal contact between the solar semiconductor cell and electrodes.

The failure of the interconnection is caused by degradation of solder joints during module's field operations due to temperature cycling. Extreme degradation often culminates in module failure. The existence of this phenomenon and the need to provide solution has been reported in [1, 6, 8-10]. The analysis of the failure mechanisms of PV modules in the field demonstrates that the modules fail by many different modes. McCluskey [7] and Campeau, et al [11] have reported that according to a BP study, 40.7% of PV module failures observed were due to cell or interconnect breakage. This finding, in addition to other similar findings, has identified the reliability of PV interconnections as the current challenge in PV modules manufacture.

Consequently, the interconnection technologies of silicon PV modules were selected for review. Silicon PV modules were chosen because the production of silicon-based solar cells was 90% of all solar cells produced globally in 2008 [3]. This production share may have been achieved because Silicon, being the second most abundantly available element on earth [12], has been used as the primary feedstock. For instance, this largest share of production was more than 90.956% of global PV module production in 2013 [13] and this share of production is expected to remain for a long time. This paper explores and characterises silicon solar cell interconnection technologies used in the various crystalline silicon solar cell manufactures.

The objectives of this study are to present an overview of crystalline silicon PV modules while dwelling on the characterisation of the solar cell contact and interconnection technologies. The work advances to seek to review the current reliability challenges of the interconnection of the solar cells with regards to interconnection technique. In addition, the paper reviews research trends in solar cell interconnection and assembly technologies - focusing on the identification of suitable technology to meet long-term reliability demand of PV modules for energy generation.

## 2. Crystalline silicon solar cells interconnection technologies

The contact and interconnection technology of conventional wafer-based silicon solar cells are discussed in sub-section 2.1 while challenges of conventional interconnection technology are presented in sub-section 2.2. A comparison of conventional and unconventional interconnection technologies is discussed in sub-section 2.3.

### 2.1 Interconnection technology of conventional crystalline silicon solar cells

The assembly and manufacturing process of conventional solar cells involves converting silicon wafers into solar cells through depositing layers of emitter material and anti-reflection coating (ARC). This process is followed by printing front metal electrode and back contacts on the cell material as well as soldering of highly conductive solder-coated ribbon strip along the length of the cell. An extended part of the ribbon strip is soldered to the back of a neighbouring cell to enable current transfer from the front of one cell to the back of a neighbouring cell in a series connection [5]. The use of low resistant electrode and finer lines for a larger aperture in the manufacture enables the delivery of higher short circuit current ($I_{sc}$) and fill factor to the ribbon strip [14]. The interconnection of solar cells in crystalline silicon modules by soldering process is a high temperature process which occurs at about 250 $^{o}$C. The elevated temperature soldering induces thermo-mechanical stress in the solder joints.

Metallization technologies in use for solar cells contact formation include: screen printing, stencil-printing, pad-printing, ink-jet printing, dispensing technology, photolithographic and evaporation process, laser micro-sintering, plating (Nickel) and thickening of metal contacts by means of plating [15]. In the photovoltaic industry, the predominant technique used for the establishment of an ohmic contact to an n-type emitter of a crystalline silicon solar cell is screen printing of an Ag-based thick-film paste and firing through the ARC layer [15-18]. A typical structure of Aluminium Back Surface Field (Al-BSF) solar cell is shown in Fig.1.

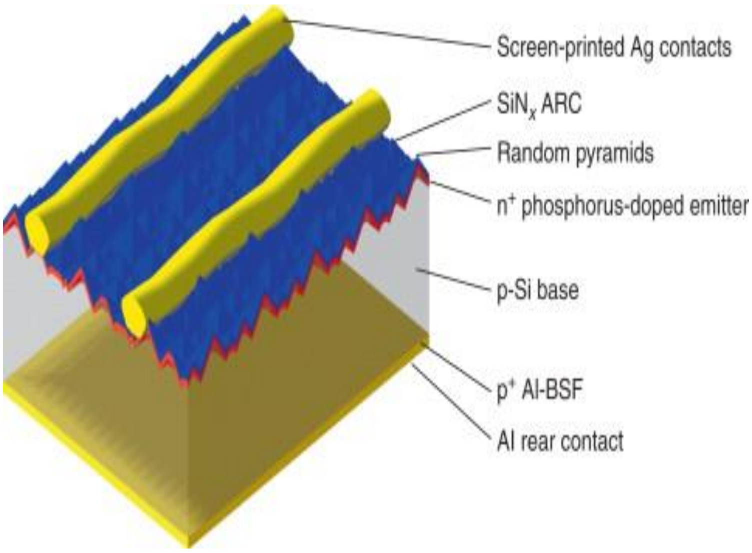



Fig.1. Typical structure of Al-BSF solar cell [16]

## 2.2 Challenges of conventional interconnection technology

The manufacture of crystalline silicon solar cells using the conventional form of assembly results in associated challenges which limit the quantity of energy generated as well as imparts the thermo-mechanical reliability of PV modules. These challenges include series resistance, shadowing losses and induced thermo-mechanical stress in the solar cells.

Series resistance losses are one of the major challenges associated with the manufacture of solar cells in the conventional form. These losses are created due to metallization for contact formation and the subsequent tabbing for current collection. In order to reduce these losses, new concepts are being developed with additional objectives of providing contacts for thinner wafers. This objective is aimed at: reducing material cost, ensuring low-stress interconnection between cells and enabling the ease of modules manufacture [19].

Another key challenge of conventional interconnection technology is shadowing losses. When cells are made wider, thicker interconnection ribbon is required to conduct larger currents. It is reported in [20] that increase in the width of interconnection ribbon cross-section increases the shadowing losses proportionally. The thickness of ribbon strip is limited by built-up stresses in the soldered joint. The differences in coefficient of thermal expansion between ribbon interconnection materials and silicon account for this stress accumulation [20, 21]. Furthermore, stress occurrence at the edge of the wafers due to bending of the interconnection ribbon strip which connects the front side with the rear of the neighbouring wafer [21] impacts the reliability of the assembly. This situation entails that conventional interconnection technology makes a compromise between width and thickness of ribbon strip. Apart from shadowing losses, there are also recombination losses which are not influenced by interconnection technologies. However, reduction of these losses is desirable to enhance solar cell efficiency. This reduction can be achieved through the use of Laser-Fired Contact (LFC) process, particularly for the rear surface, to fabricate solar cells with a high quality rear surface [15, 22].

Induced thermo-mechanical stress in the solar cells is another challenge associated with the manufacture of solar cells in the conventional form. The manufacturing process of interconnecting wafer-based silicon solar cells involves the use of infra-red (IR) reflow soldering. The soldering process consists of two phases. These are stringing or tabbing as well as bussing. The former involves the interconnection of solar cells with each other to form strings while the later deals with the assembly of the strings of solar cells to form PV module [23, 24]. However, this interconnection procedure is difficult and the IR soldering induces high mechanical stress in the solder joint which accelerates fatigue related damage. Eventually, module failure occurs during field operations thereby halting energy generation. Figure 2 presents a diagram of solder interconnection between tabbing ribbon and conventional wafer-based crystalline silicon (c-Si) solar cells while Fig. 3 depicts a schematic of a typical laminated crystalline Si solar cell showing its cross-section. Figure 4 shows typical interconnected solar cells with tabbing and bussing ribbons while Fig. 5 shows a typical PV module with complete interconnected solar cells.

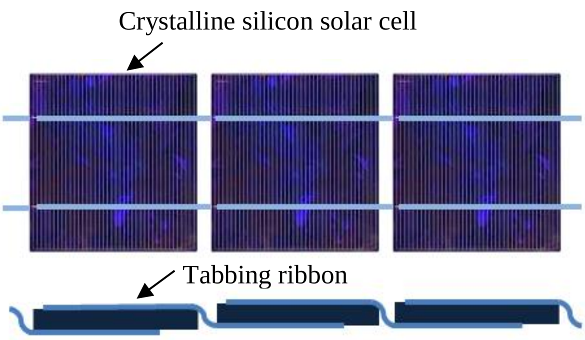



Fig. 2. Crystalline silicon solar cells interconnected in series with tabbing ribbon

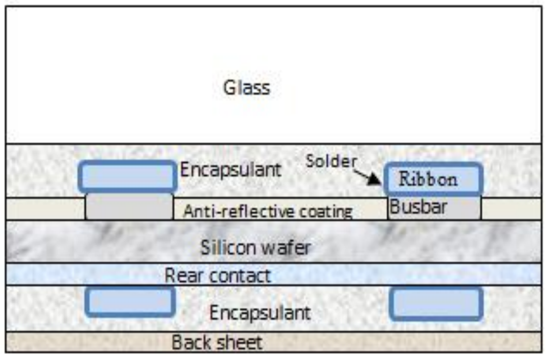



Fig. 3. Schematic of cross-section of a typical laminated crystalline Si solar cell.


Fig. 4. Interconnected solar cells with tabbing and bussing ribbons [25]

Fig. 5. PV Module with complete interconnected solar cells [23]

In order to address some of the challenges of crystalline silicon solar cells interconnection using IR soldering, laser soldering technology is used because it offers some advantages. Laser soldering is well controlled and enables selective processing. Additionally, when used for spot soldering, it delivers heat very fast, precisely and efficiently on a small area of the solder interconnection without making physical contact with the brittle crystalline silicon solar cells. Since physical contact during soldering can result in cell breakage, laser soldering has demonstrated potentials of inducing minimal thermo-mechanical stresses on the solder joint as well as less probability of causing cell breakage during manufacture which will increase production yield [26].

## 2.3 Comparison of different interconnection technologies

In order to address the interconnection challenges, many unconventional PV modules with improved interconnection have been developed. Their interconnect concepts include back contact cells technology. In this technique, the interconnection materials and circuitry are located exclusively behind the cells. Examples include emitter wrap-through (EWT), metallisation wrap-through (MWT) and back-junction back-contact (BJBC). Other cell/module concepts are alternate p- and n-type, honeycomb design (HD), pin up modules (PUM), sliver, spherical and cells with flexible electrode wire grid (Day4 Electrode).

Back contact solar cells which include EWT, MWT and BJBC use in-plane interconnectors for interconnection of neighbouring cells [27]. The advantages of these cells over their conventional counterpart include: possession of reduced stress in the soldered joint, possession of minimal shadowing loss caused by metal grids, provision of more surface area for current generation, optimisation of module efficiency and improvement of aesthetics of the module [20, 28, 29].

Alternate p- and n-type silicon solar cells are bifacial screen-printed cells which use alternating p- and n-type semiconductor devices thereby allowing direct interconnection of equivalent sides on front-to-front and back-to-back of neighbouring cells [30]. The advantages of this solar cell technology compared to their conventional equivalent include simpler interconnection procedure, closer assembly of cells (for aesthetic reasons) and higher yield during module fabrication.

Honeycomb design (HD) solar cells are cells made with surface texturing that resembles honeycomb structure. This type of design provides very effective light trapping in the cell by total internal reflection. The honeycomb texturing reduces surface reflection of the solar cells [31,32]. The interconnection of the thin HD crystalline silicon solar cells is achieved through the use of an integrated series-connection structure.  The advantage of HD cell concept is that series resistance losses are reduced due to removal of areas with contact resistance which are present in conventional cells.

Pin up modules are back-contacted solar cells designed with a structured interconnecting back foil and limited number of holes in the wafer. The holes are used as vias and contain pins serving as interconnection from the front-side metallisation to the interconnection material at the rear [21, 33]. The advantages of Pin up modules over conventional modules include possession of minimal series resistance and shadowing losses.

Sliver cells are perfectly bifacial monocrystalline silicon solar cells. These cells are long, narrow, thin and symmetrical in appearance. The technology employed in the fabrication of these cells promotes economy in the usage of silicon materials. A decrease of about 10 to 20 times the quantity of silicon used in other conventional technologies is obtainable when sliver cells technology is utilised [34]. The sliver cells are interconnected with two thin, narrow substrate supports to form a conventional solar cell analogue. The cells are thin with collecting junctions on both surfaces and the contacts are on the rear of the cell [35].  The advantage of sliver cells concept is that shadowing losses are minimised compared to conventional crystalline cells.

Spherical silicon solar cells capture light from all directions because of the spherical geometric nature of the reception surface. This design feature has the capacity to improve the amount of power the system generates to the maximum [36]. The benefits of spherical solar cells include less silicon usage, lower cost and usable in a variety of applications [37]. The spherical cells are interconnected adjacent to one another to form a mini-module in series which produces a specific constant voltage; and current which may be varied. A key advantage of spherical cells over conventional crystalline cells is that shadowing losses are effectively eliminated.

Silicon cells with flexible electrode wire grid (Day4 Electrode) structurally consists of transparent polymeric film, a layer of adhesive and embedded copper wires coated with low melting point alloy [38] which interconnects the cells with copper wires. The copper wires are very tiny and embedded in the transparent film. This arrangement has the advantage of minimal shadowing effect predominant in the conventional crystalline cells.

Although IR and laser soldering technology are used in several cell concepts, they are not the only interconnection techniques. Techniques which include ultrasonic welding [39], thermal spraying [40] and conductive adhesives [41] have been successfully employed. Each of these techniques induces thermo-mechanical stress in the solder joint to some degree. The techniques create series resistance and shadowing losses in the solar cell. Moreover, these techniques induce thermo-mechanical stress in the interconnection joint. The mechanism of thermo-mechanical stress origin is dependent on the difference between solder melting temperature and room temperature. This conveys the concept of homologous temperature of material. Homologous temperature expresses the temperature of a material as a fraction of its melting point using the Kelvin scale. At low homologous temperatures, joint materials of interconnected solar cells are structurally modified and residual intrinsic stresses are induced in the joint. On the other hand, processing temperature for each interconnection technique is different. The typical reflow temperature for tin-silver-copper (SnAgCu) solder used for interconnection of conventional front-to-back cells is about 250 $^{o}$C [42]. Similarly, processing temperature for laser spot soldering of cells is about 225 $^{o}$C [26] while for ultrasonic welding, the temperature is about 177 $^{o}$C [43]. Likewise, the processing temperature for interconnection of cells using thermal arc metal spraying and conductive adhesive is about 150 $^{o}$C [40] and 125 $^{o}$C [41] respectively.

Interconnection of solar cells results in bonded materials at the interconnection joint. In order to ensure that the bond has adequate strength, the bond is tested to determine its peel force. Peel force is the measure of adhesion strength required to part bonded materials. The interconnection concepts developed and their corresponding interconnection techniques with peel force and residual stress are presented in Table 1. It can be observed in the table that some interconnection concepts have more than one interconnection technique. It therefore serves as a reference guide to PV manufacturers who may be interested in making choices of technique to use when consideration on peel force and induced residual stress in the solder joint are factors.

Table 1: Comparison of different interconnection techniques with peel force and residual stress for various interconnection concepts employed in assembly of crystalline silicon solar cells

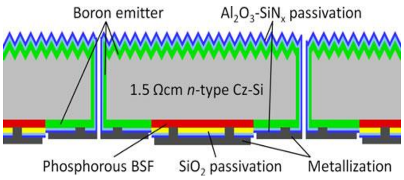
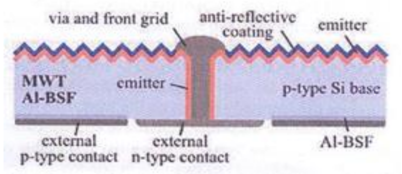
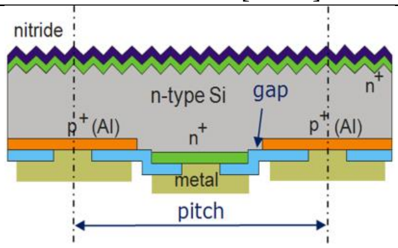
| Interconnection concept | Inter-connection technique | Peel force (N) | Residual stress (MPa) |
|---|---|---|---|
| <br>Conventional front-to-back cell interconnection [24].<br><br>Tabbing ribbon soldered to front and back of cell [25, 26]. | IR soldering<br>-------------------------<br>Laser spot soldering | 2-16 [44]<br>------<br>1-5 [46, 47] | 49-359 [45] (Simulation)<br>---------------<br>NA |
| <br><br>Back-contact EWT solar cells [48].<br><br>Hole drilled for vias which allow emitter wrap through from front of the cell to the back surface [27-29, 48, 49]. | Laser soldering<br>-------------------------<br>Conductive adhesive | 1-5 [46,47]<br>------<br>0.3-1 [50] | NA<br>---------------<br>15-19.5 [51] (Simulation) |
| <br><br>MWT solar cells [53].<br><br>Similar to EWT cells but has metal grid contact on the front surface while interconnection pads for both polarities are on the rear surface [52-54]. | Laser soldering<br>-------------------------<br>Conductive adhesive | 1-5 [46, 47]<br>------<br>0.3-1 [50] | NA<br>---------------<br>15-19.5 [51] (Simulation) |
| <br><br>BJ-BC solar cells [55]<br><br>Both emitter and metallisation are located at the rear surface of the cell [55, 56] | IR soldering | 2-16 [44] | 49-359 [45] (Simulation) |

Table 1 (Continued)

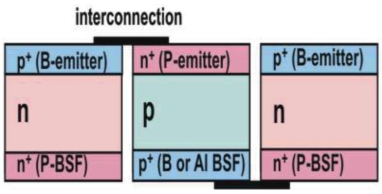
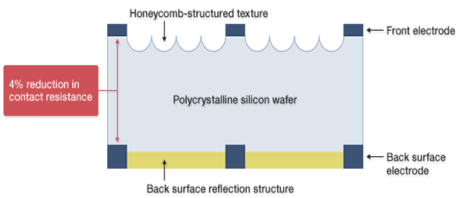
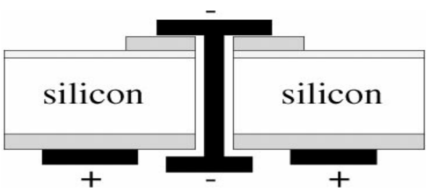
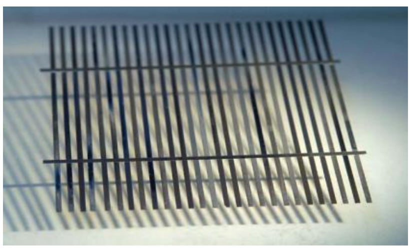
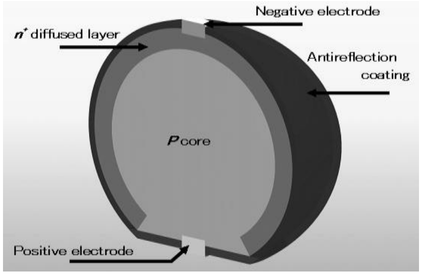
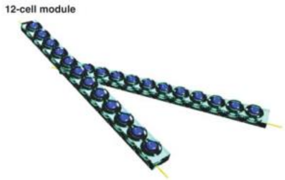
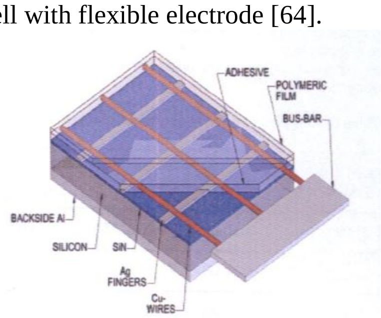
| Interconnection concept | Inter-connection technique | Peel force (N) | Residual stress (MPa) |
|---|---|---|---|
| <br>Alternate p- and n-type silicon solar cells [30].<br><br>These bifacial cells allow direct interconnection of equivalent sides on front-to-front and back-to-back of neighbouring cells [30]. | IR soldering | 2-16 [44] | 49-359 [45] (Simulation) |
| <br>HD solar cell [58]<br><br>Interconnection of the thin HD cells is achieved through the use of an integrated series-connection structure [31, 32, 57, 58]. | IR soldering<br>-------------------------<br>Conductive adhesive | 2-16 [44]<br>------<br>0.3-1 [50] | 49-359 [45] (Simulation)<br>----------------<br>15-19.5 [51] (Simulation) |
| <br>PUM Cell [33].<br><br>Interconnection from the front-side metallisation to the interconnection material at the rear achieved through vias containing pins [33, 59]. | IR soldering<br>----------------------<br>Thermal arc metal spraying | 2-16 [44]<br>------<br>NA | 49-359 [45] (Simulation)<br>----------------<br>NA |
| <br>Sliver cells [34, 35].<br><br>Cells interconnected by two thin, narrow substrate supports [34, 35]. | Solder bumps | 1-5 [46, 47] | NA |

Table 1 (Continued)

| Interconnection concept | Inter-connection technique | Peel force (N) | Residual stress (MPa) |
|---|---|---|---|
| <br><br>Spherical cell [36].<br><br><br>Interconnected spherical cells [37].<br><br>Cells are interconnected adjacent to one another to form mini-modules which in turn are interconnected by ultrasonic welding [36, 37, 60, 61]. | Ultrasonic welding | 2-5 [62] | NA |
| <br>Cell with flexible electrode [64].<br><br><br>Cell in contact with electrode [65].<br><br>Interconnection achieved using flexible Day4 electrode wire grid consisting of transparent polymeric film, a layer of adhesive and embedded copper wires coated with low melting point alloy. The wire grid is glued to the cells using adhesives to obtain interconnection [38, 63-65]. | Conductive adhesive | 0.3-1 [49] | 15-19.5 [50] (Simulation) |

Furthermore, interconnection technologies for silicon solar cells are numerous and have various applications. The conventional interconnection concepts remain dominant while the other concepts are completely unconventional and modest. The review found some concepts which combine conventional with other concepts. For instance, on-laminate laser soldering (OLLS) was developed to combine the reliability potentials of conventional module assembly with the smoothness potential of the process steps in the monolithic module assembly (MMA) [66, 67]. The concept involves interconnecting solar cells on a patterned back sheet foil using conductive adhesives or low melting point solders [68].

Table 2 presents a comparison of interconnection technologies employed in the manufacture of silicon solar cells including thin-film silicon solar cells. The index of comparison is cell type, joint type and production status. It can be observed from the table that conventional interconnection technologies for wafer-based silicon solar cells and for thin-film silicon solar cells are the only widespread and commercially available technologies. New concepts used in solar cells interconnection are either partially available or are yet to be commercially available.

Table 2: Comparison of silicon solar cells interconnection technologies in terms of cell type, joint type and production status

| | | Cell type | Interconnect technology | Joint type | Production status: Widespread | Partially | R & D |
|---|---|---|---|---|---|---|---|
| Silicon solar cells | Wafer-based | Conv. c-Si and mc-Si | Ribbon (front-to-back) | Solder joint | ✓ | | |
| | | Alternate p- and n-type | Ribbon (equivalent sides) | Solder joint | | | ✓ |
| | | EWT | Edge tab (back contact) | Solder/ conductive adhesive joint | | ✓ | |
| | | MWT | Conductive foil/Ribbon | Conductive adhesive/ Solder joint | | ✓ | |
| | | EWT, MWT | Bone-shaped interconnector (MMA) | Laser solder joint | | | ✓ |
| | | Honeycomb design | Ribbon/Adhesive | Solder/ conductive adhesive joint | | | ✓ |
| | | PUM | Foils with patterned conductors | Solder/thermal metal spraying | | | ✓ |
| | | Sliver | Substrate support bond | Solder joint | | ✓ | |
| | | c-Si and mc-Si | Day4 electrode | Day4 electrode adhesive joint | | ✓ | |
| | Cz. Si | Spherical | Substrate support bond | Ultrasonic Welded joint | | ✓ | |
| | Thin-film | Conv. a-Si and μc-Si | Monolithic series | Conductive film bond | ✓ | | |

## 3. Interconnection materials and technology reliability challenges of silicon solar cells

Although it is reported in [69] that the reliability status of PV systems is good, even with a reliable technology there is always room for improvement. With the reported recent cases of unprecedented failure of PV modules in the tropics, the improvement of reliability of modules has become essential more so as the improvement will encourage more system uptake. System's reliability depends to some extent on their cost of manufacture and it is measured by parameters which include systems performance, availability and degradation during operation and maintenance (O&M) and predictability [70] as well. It has been widely reported that the daily thermal cycles which PV modules are subjected to in the field is one of the causes of degradation experienced by its interconnection. In addition to accelerating interconnect degradation; the thermal cycling also increases series resistance [71]. As discussed previously, silicon solar cells are interconnected with one another either by the process of soldering or by the use of electrical conductive adhesive [72]. The reliability challenges of each technique are widely reported by researchers. In this section, this review will present and discuss the challenges associated with these two techniques. It will discuss the reliability of interconnection made using solder in sub-section 3.1 while in sub-section 3.2, it will discuss the reliability of interconnection made using electrical conductive adhesives.

### 3.1 Reliability of solder interconnection in PV modules

The key materials used in the assembly of conventional crystalline silicon modules include silicon, glass, copper ribbon, back sheet, encapsulant, bus-bar and solder [24]. A critical part of the module is the solder joint interconnections. They consist of many materials bonded together. The materials bonded together in the joint are the solder, bus-bar, ribbon and the silicon wafer. These materials possess different thermal and mechanical properties. In bonding, the assembly develop thermo-mechanical reliability issues which are caused by differences in the bonded materials' coefficient of thermal expansion (CTE). In PV module solder interconnection, the solder provides a connection between the electrode and ribbon. This connection is the pathway through which current flows from the silicon semiconductor to the ribbon. The PV module temperature varies according to local weather which in turn affects the rate of solder interconnection degradation. In a lifetime prediction modelling analysis [73], Han et al reported that for the same type of Si PV modules located in various weather conditions, lifetime was shortest in a desert followed by those in the tropics.

Although the use of soldering process in the assembly of solar cells in PV modules has the advantage of yielding products which possess high reliability at minimal production cost, the technology occurs at high temperature with inherent potential to produce shear stress in the silicon wafer. This occurrence which is due to the differences in CTEs of the bonded interconnect materials in the assembly [74] may result in systematic grid finger interruptions at the bus-bar edges [24, 74] and also fatigue damage. In the presence of transients associated with passing clouds and daily thermal cycling, the joints are exposed to fatigue loading which leads to metal segregation, grain boundary coarsening/cracking and increased series resistance and heating [7, 75, 76]. Some approaches have been proposed to either reduce or avoid these reliability issues which have been discussed and presented earlier in unconventional interconnection concepts.

Interconnection technologies involving the use of laser soldering for interconnecting solar cells have been developed by researchers for various concepts of PV modules. Utilising laser soldering technology for interconnection has the potential to ensure that the joints are highly reliable when compared to conventional soldering technology. This is because laser soldering induces minimal thermal and mechanical stresses in the solder joints. In an experimental investigation [77], Schmidhuber et al reported that peel force in conventional soldered tabs was in the range of 1 to 3 N while that in a laser soldered tabs is about zero. This finding supports the earlier statement that laser soldering has minimal mechanical damage in the solar cell interconnection. Therefore, the adoption and use of laser soldering technology to interconnect crystalline silicon cells need to be explored as a replacement for conventional soldering technology for improved reliability of solder interconnections in crystalline PV modules.

### 3.2 Reliability of electrical conductive adhesive interconnection in PV modules

The elevated temperature soldering of cells induces stress in the cells. In addition to the induced stress, the solder joints are also stressed and deformed during operations in the field. The deformation of the joints culminates in cell warpage, breakage and ultimately system failure at prolonged operations.

To avoid this situation, some manufacturers use electrical conductive adhesives in place of solder for the interconnection. The electrical conductive adhesives, which are made of silver-loaded epoxy resins, are being used successfully as an alternative bonding material for solar cells interconnection [78]. The use of conductive adhesives as an alternative to solder has been shown to have minimal change on the mechanical properties of the bonded materials in the joints. Similarly, its use enhances the conductivity of the joint. As this bonding process is carried out at low temperature, it leaves minimal residual stress on the joint with advantage of minimal cell breakage [78, 79]. It is pertinent to note that conductive adhesives can be used for interconnecting both crystalline and thin film solar cells.

Although the adoption and use of this low temperature bonding technology appear to solve the initial challenge encountered in using soldering process, there are some key reliability challenges associated with modules manufactured using the process during field operations. The adhesives undergo accelerated degradation occasioned by oxidation of the adhesive material. Moreover, the adhesive-to-metal bond, which is the interconnection joint, experience de-bonding [78, 80]. The de-bonding commences with crack initiation and propagation which enables corrosion induced system failure.

## 4. Future R&D challenges and opportunities

While several crystalline silicon module concepts have been developed to address the various challenges discussed earlier, there is no single concept that has solved all the challenges. Therefore, opportunities exist for more research and development (R&D) for further improvement of the cells design and manufacture. In this regard, R&D opportunities focussed on series resistance, shadowing and recombination losses as well as induced thermo-mechanical stress are discussed as follows.

Series resistance losses in a crystalline silicon solar cell have three main causes. The first cause is the current flow through the emitter and base of the solar cell while the second cause is the contact resistance between the metal contact and the silicon. The final cause is the resistance of the top and rear metal contacts. In addition, it is also known that thermal cycling increases series resistance. Considerable R&D is required aimed at reducing series resistance losses through the decrease in metal contact resistivity which can improve energy conversion efficiency of the cells.

Shadowing losses result from interconnection ribbons placed on the surface of wafer-based crystalline silicon cells. Their presence on the cell surface occupies precious space thereby preventing power generation by that cell portion. Increase in the width of interconnection ribbon cross-section increases the shadowing losses proportionally. The best situation will be to completely relocate the interconnection to the back of the cell. This desire forms the basis for back contact cell concepts. However, the fabrication challenges associated with these concepts has affected the uptake of the technology. Furthermore, the reliability of these concepts is yet to be proven in long-term field exposure. Thus, the R&D opportunities for reduction of shadowing losses include simplification of fabrication processes and ensuring solar cells developed are durable and reliable.

Induced thermo-mechanical stress in PV modules is a concern that requires proper attention. Photovoltaic module interconnection consisting of solder joints, ribbon and busbar are found to be the most vulnerable part to degradation and failure. As mentioned earlier, the differences in CTE among these bonded materials and long repeated temperature cycles induce thermo-mechanical strain and stress in the joint. These factors lead to module untimely failure which becomes aggravated in poor solder bonding between ribbon and silver busbar. Concerted R&D is needed for the optimization of the parameter settings involved in manufacture of these modules to improve the reliability of PV module assembly. These parameters are the dimensions of the ribbon, busbar, backsheet and any other critical dimension identified. The application of finite element modelling in the early design stage of PV modules has the potential to predict the response of the assembly to cyclic thermo-mechanical stresses and strains. The techniques could also be used to determine the optimal parameter settings of the control factors in the module assembly. This will enable the determination of an optimal parameter setting of solder joint to improve the thermo-mechanical reliability of PV module assembly. Additionally, more R&D is required for conductive adhesives used for solar cells interconnection in order to improve their durability and reliability.

## 5. Summary

A review of contacts and interconnection technologies used to assemble crystalline silicon solar cells has been presented and discussed in this paper. The review was extended to include detailed description of the concepts and interconnection technologies employed in the manufacture of unconventional silicon solar cells.

It was found that the predominant interconnection technology used in the manufacture of wafer-based silicon solar cells involves soldering of ribbon on the surface of cell. This basic technique is shown to be none ideal because the soldering process induces thermo-mechanical stresses in the cells and joints. The review results show that the process of interconnecting ribbon on the front-to-back surface of the cells leads to significant series resistance, shadowing losses. It identifies the technology of laser soldering as one which is poised to produce high reliability interconnection joints in the module. The capacity to heat only very small area of the ribbon placed on the cell enables the laser technology to induce minimal stress on the cell and joints after soldering and consequently produces quality assembly. On the other hand, it was found that adhesive-to-metal bond experiences substantial crack initiation and propagation which enables corrosion induced system failure. More review results indicate that the concepts developed for unconventional solar cell (to address the current reliability issues in the manufacture of PV modules) are yet to attain popular uptake because of lack of track record, major changes in tooling and manufacturing facilities as well as their attendant cost.

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