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ASSESSMENT OF THERMO-MECHANICAL FAILURES OF PHOTOVOLTAIC MODULE COMPONENTS FOR IMPROVED RELIABILITY

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ABSTRACT

Although the production and utilization of photovoltaic (PV) modules continue to grow monotonically, the long-term reliability of these modules still remains a concern due to untimely failure. The breakdown of the module is induced by thermo-mechanical fatigue loading caused by temperature cycling as well as transients associated with passing clouds. This paper evaluates the failure mechanism of PV module assembly in operation with a particular focus on the assessment of the mechanics of failure of its integral components. It discusses the failure mode of solar cell interconnections, packaging materials and other components with a view to presenting ways of improving the assembly thermo-mechanical reliability. Based on the evaluation of thermal cycling tests and field failures of some modules, this study found that solder joint failure is the most critical. Further analysis of the structure of PV solder joints reveals that the growth of the intermetallic compound (IMC) in the solder joint during the operation of the PV module contributes significantly to the failure of the module. Therefore an in-depth understanding of the formation of IMC in solder joint is necessary. Also, the inclusion of IMC in the model employed to simulate and analyze the module failure mode offers potential to providing vital information which when utilized can result in the manufacture of systems with increased thermo-mechanical reliability and mean-time-to-failure (MTTF).

KEYWORDS: *Crystalline Silicon Solar Cells; PV Modules; Reliability; Thermo-Mechanical Failures*

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INTRODUCTION

The increase in acceptance, adoption, and use of photovoltaic (PV) modules to generate electric power has boosted the availability of electrical energy to widespread applications. Such applications are found in our homes, offices, and environments. In these places, electrical energy from PV modules is used to power water pumps, night lights, clocks, communications, and weather monitoring equipment, satellites and space vehicles as well as a variety of other applications [5]. These applications have resulted in their huge demands and have initiated consistent growth in PV module production. If the growth continues as projected, by around 2020, the world annual production of PV cells will be around 100GW$_p$ (W$_p$, is peak power produced under standard test conditions) [6]. In order to further encourage the adoption and utilization of PV modules, it is essential that their reliability is improved.

Mc Cluskey [7] and Kato [8] have reported that PV modules are failing to continually perform up to 20 years of their design life span during field operations due to untimely failure of some module components. The failure to continually generate electricity by the PV modules in the field is a concern [9-12] because of such failure may lead to catastrophic consequences. The enhancement of reliability, availability, and durability of module components is now more critical, especially for mission-critical systems. The generation of electricity from PV modules depend on local weather which also affects their lifetime. For instance, a module in desert weather is expected to have a shorter lifetime compared to the one in either a tropical or temperate weather. Han, et al. [9] have reported similar observation. Higher temperatures in the desert cause faster degradation of the module. Studies by Jeong et al. [9], Sakamoto et al.[12], Jeong et al. [14], Skoczek et al. [15] and Granata, et al. [16] indicate that diurnal cycle of temperature imparts on the PV modules during field operations causing degradation which eventually result in failure of the PV module. Irrespective of weather condition, PV modules undergo degradation whenever they are exposed to daily sunlight due to thermal loading. In addition, Betts [13] reported that in the majority of situations, passing clouds often cause more than 20 ^{o}C temperature variation multiple times during the day, while the diurnal cycle causes in the range of 12 ^{o}C variation once over a 24 hour period. The effects of these variations cause IMC to form and grow in the interconnection whilst the assembly experiences thermal cycling which leads to thermo-mechanical fatigue loading. Such loading degrades the device and caused component and subsequently module failure.

The foregoing situation cause the failure of solar cell interconnections, packaging materials and other components of the PV modules. Therefore, this study is conducted to produce vital information for the improvement of thermo-mechanical reliability of PV module assembly thereby enabling greater availability and longer lifespan.

Thermo-Mechanical Failure Mechanism of PV Modules

To attempt to characterize the reliability and durability of PV modules, the fundamental mechanisms which cause failure need to be considered[17]. The reliability of the complete PV module system depends on the reliability of each of its component parts. The most critical constituents of the crystalline silicon (Si) PV module in terms of reliability involve solar cells interconnects comprising solder joint, cell interconnection ribbon, and busbar. The interconnections provide electrical, mechanical and thermal contact for the solar cells. Other critical components include the semiconductor device and packaging materials. This paper presents an overview of the dominant failure modes due to thermo-mechanical loading in crystalline silicon PV module components. The main focus of this study is the reliability concerns associated with daily thermo-mechanical loading of the PV cell interconnects.

Structurally, crystalline silicon PV module consists of several components which are subjected to thermo-mechanical loading during service operations. The module structure highlighting the relationship of each component to the other is presented in Figures. 1 to 4. Figure. 1 is a typical multi-crystalline solar cell. It consists of a cover plate (glass), encapsulant, solder coated ribbon, antireflective coating, the semiconductor device (silicon wafer) and back sheet. Solder is used to connect conducting ribbon to the solar cell bus-bar (front contact) such that the solder joints provide electrical, mechanical and thermal interconnection between the silicon wafer and the conducting ribbon which in turn interconnects the front surface of one cell to the rear surface of a neighboring cell [4, 6, 14, 18-20]. Figure. 2 depicts crystalline silicon solar cells interconnected in series with tabbing ribbon while Figure. 3 portrays a schematic of solder interconnection between ribbons of wafer-based crystalline silicon solar cells. The schematic of a cross-section of a typical crystalline silicon solar cell is presented in Figure. 4. As the material composition of each module component is different, when subjected to the same thermo-mechanical load, the modules show a significant difference in their failure mode and mechanism. In the crystalline silicon module shown in Figure. 2b, it is easy to observe that the geometry of copper ribbon will pose stress riser issues in the interconnection. The degree of the "z" shape formed between the cells depends on the thickness of the silicon cells. Consequently, the geometric analysis of module assembly is critical in obtaining information necessary to improve the reliability of the system.

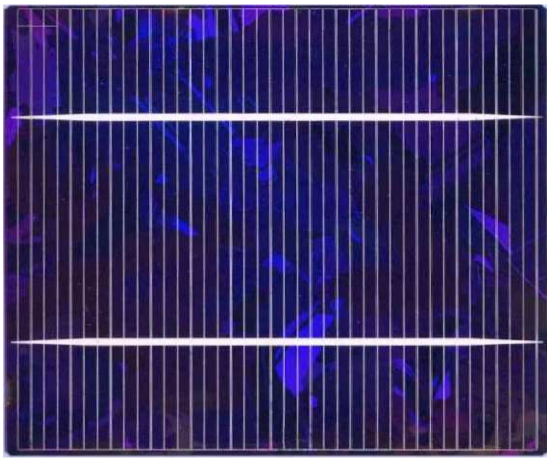

Figure 1: Typical Crystalline Silicon Solar Cell

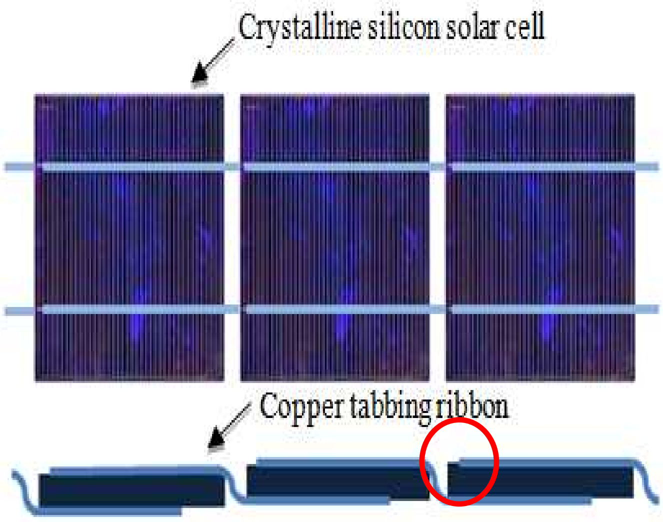

Figure 2: Crystalline Silicon Solar Cells Interconnected in Series with Tabbing Ribbon: Plan View and Side View

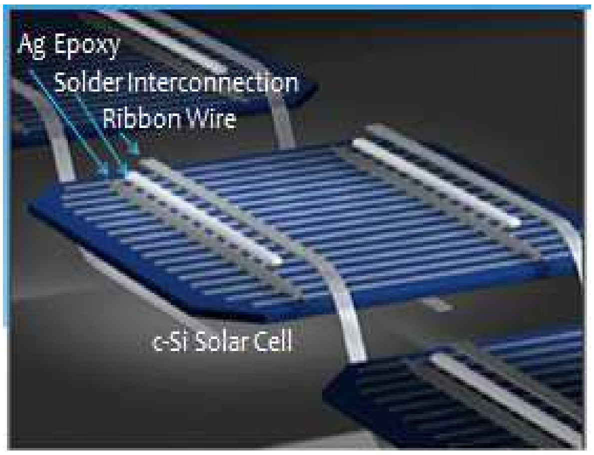

Figure 3: Schematic of Solder Interconnection between Ribbon Wires and Wafer-Based Crystalline Silicon Solar Cells [8]

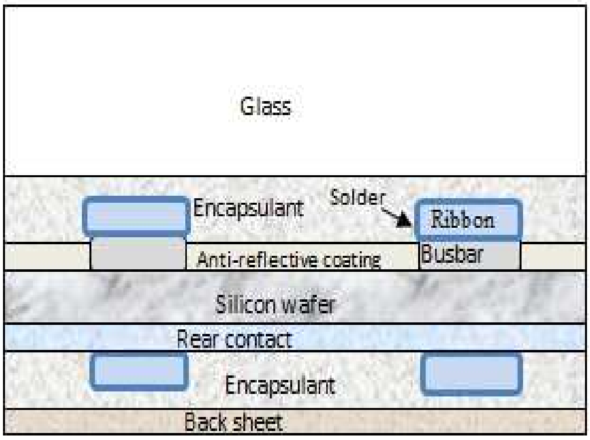

Figure 4: Schematic of Cross-Section of a Typical Laminated Crystalline Si Solar Cell

Presented in Table 1 are typical component materials used in laminated crystalline PV silicon modules as well as material thickness and coefficients of thermal expansion (CTE). As the Table shows, the CTE of ribbon, solder, busbar, and Si cell are different. The range of CTEs for module component is from 2.6×10^{-6}/K for monocrystalline silicon cell to 30×10^{-6}/K for Tedlar back sheet. This indicates a range of CTEs of magnitude more than 10 times from components with the least value of CTE to the one with the highest value of CTE. The variation causes large mismatch in the thermal expansion and contraction that to occur during module operations and which induce mechanical stresses in the module[4].

Table 1: Typical Component Materials used in Laminated Crystalline Silicon PV Modules [2, 5, 7, 15,16,18]

Component	Typical Material	Thickness (μm)	CTE (10^{-6}/K)
Solar cell	Mono crystalline silicon	160-240	2.6
Cover plate (Illuminated side)	Glass	3000-4000	10
Encapsulant	EVA	460-500	15
Anti-reflective coating (ARC)	Titanium Oxide (TiO_2)	0.05-1.54	8-10
Solder	96.5Sn/3.5Ag 95.5Sn/3.8Ag/0.7Cu	0.5-50 0.5-50	20.2-21.7 17.6-23.2
Ribbon	Copper (Cu)	75-200	16.5-17
Busbar (Front contact)	Silver (Ag)	25-50	18
Rear contact	Aluminium/Silver (Al/Ag)	15-40	11.9
Back sheet	Tedlar	100-190	30

Thermo-mechanical stresses degrade PV modules during field operations and ultimately lead to failure. McCluskey [7] reported that Wohlgemuth conducted a survey of field returns of BP Solar modules and found that stressors such as thermal expansion or contraction caused cell or interconnect break; this failure type accounted for 40.7% of all failures observed. TamizhMani and Kuitche [19] documented failure modes in PV modules resulting from thermo-mechanical fatigue to include broken interconnects, broken cells, solder bond failures, junction box adhesion and module connection open circuits. Additionally, thermal cycling facilitates several other potential failure modes in the module. This indicates that thermo-mechanical fatigue is a major failure mechanism which affects several module components. In section 3, failure of PV module interconnects; packaging materials and other components are discussed with regards to thermo-mechanical fatigue.

Failure of PV Module Interconnects

Thermo-mechanical stressing of PV module interconnects causes fatigue in the solder joints, ribbon and busbar. The fatigue eventually results in their failure. This section discusses the failures of these interconnects in three sub-sections.

Failure of Solder Joint in PV Module Interconnect

In Figure.3, it can be observed that solders are used as interconnect material between ribbon and silicon wafer via busbar. For many years of crystalline silicon solar cell production, lead-based solders were used for the interconnection. However, lead (Pb) based solder is hazardous to health, hence the need for a transition from Pb-based solder to Pb-free solder as interconnection material. Some typical lead-free solders used in industry for PV module production are listed in Table 1. During field operations, PV modules are exposed to daily thermal cycling which may eventually lead to solder joints failure. This failure mechanism is caused by fatigue loading of the joint and it is time-dependent. An illustration is shown in Figure. 5. It is an SEM image of fatigue damage in solder interconnection which has been subjected to long-term field operations. Fatigue degradation in solder interconnects is caused by repeated operational and environmental elevated temperature excursions [4]. These excursions induce cycles of stress in the joint. The induced stress arise is occasioned by the differences in CTE of the bonded materials which includes ribbon, busbar, and solder materials. There are many observable phenomena associated with this type of loading. The interconnection could experience metal segregation, grain boundary coarsening/cracking, increased series resistance and heating. These observations cause loss of connection [7, 21] which has been classified as a type of failure mode. This situation is worse when the solder bond is poor. Thus, proper solder bond need be made especially with lead-free solders which have about 40^{o}C higher melting point than lead-based solders [21].

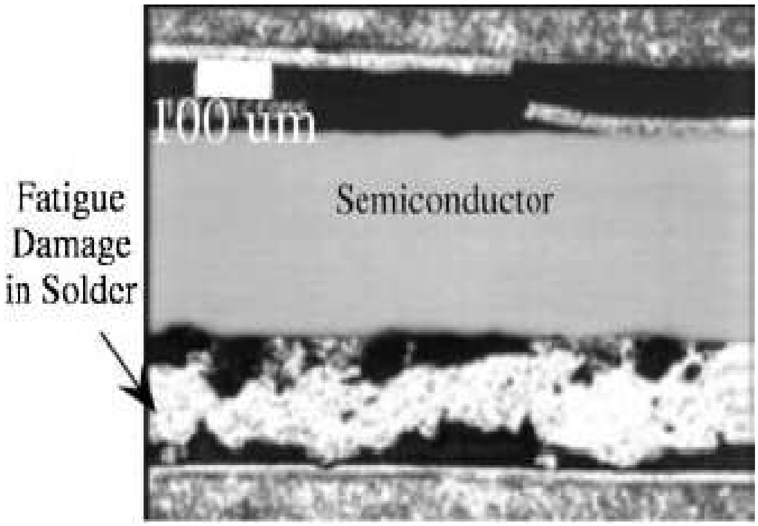

Figure 5: SEM Image of Snpb Solder PV Cells Subject to Long-Term Field Exposure Showing Significant Solder Fatigue Damage [4]

Improving the number of cycles to failure of the solder joint is desirable for reliable module performance. As recommended by Wohlgemuth, et al [22], the use of multiple solder bonds on each tabbing ribbon as well as the use of softer ribbon and provision for stress relief are ways for alleviating solder bond failures. Solder joints in PV modules should be designed for reliability by careful consideration of reliability issues at every stage of the module development and control of manufacturing processes to ensure quality assurance.

Failure of Ribbon in PV Module Interconnect

Ribbons are used for interconnecting solar cells to each other and one another. They are commonly made of copper. Figure 6 depicts a schematic of a typical build-up of a standard crystalline PV module in which solar cells are interconnected with “z’’ shape form ribbons. The ribbon and other module components are encapsulated with a flexible layer of EVA. The assembly is covered with a glass sheet. During operations, the assembly is subjected to cyclic thermal loading which causes expansion and contraction of the interconnection.

Owing to differences in the magnitude of CTE of the different bonded materials in the interconnection, uneven expansion and contraction occurs in the joint. This occurrence sets up thermo-mechanical stress in the joints between the encapsulant, ribbon, solder, busbar, and the silicon wafer. Mechanical stress in the joint could cause displacement of solar cells and loading of solar cell interconnectors in between [23]. The magnitude of this stress depends on both the material used in making the ribbon and the geometry of the ribbon[24]. During the temperature cycling and at the lowest dwell regions, the ribbon contracts to induce maximum strain on the sections of the ribbon with “z’’ shape. The process, in turn, induces maximum stress at the same location.

Thermo-mechanical stressing of the copper ribbon generates a region of hardened material which accelerates the damage of the interconnection. Majority of the forms of damage is nucleation of micro-cracks that combine to form large crack which subsequently propagates as the temperature cycling progresses. At prolonged operation, the propagating crack may traverse the cross-section of the ribbon causing ductile fatigue fracture of the interconnection [22]. This observation is represented in Figure. 7 which shows ductile crack propagation through a copper ribbon.

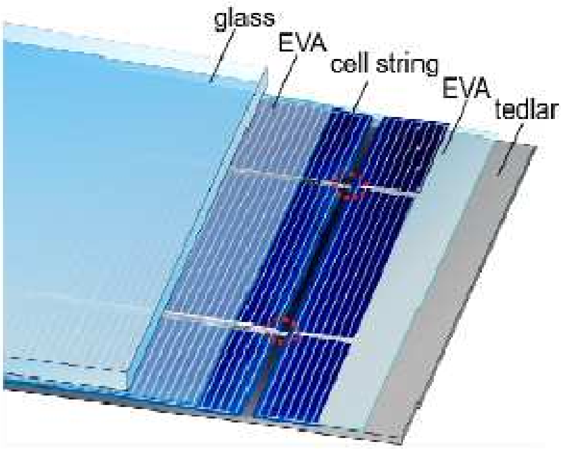

Figure 6: Schematic of a Typical Build-Up of a Crystalline PV Module (the Red Ellipses Indicate the Critical Areas for the Ribbons) [22]

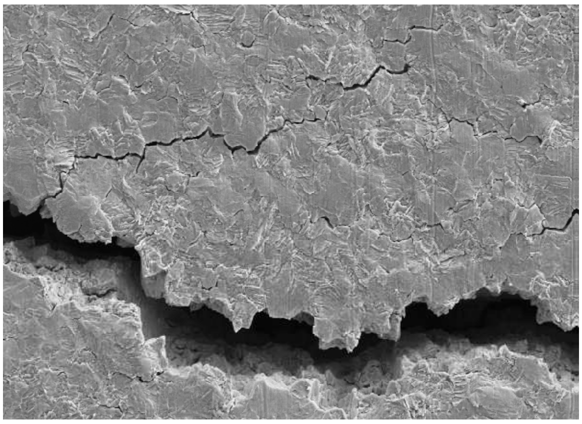

Figure 7: Ductile Crack Propagates through a Copper Ribbon [22]
the Critical Areas for the Ribbons) [22]

Crack initiation and propagation is not the only mode of failure of ribbon in the PV module interconnect associated with discontinuity in the interconnection. Discontinuity is also reported to be caused by delamination of copper ribbon. Such delamination causes loss of physical and electrical contact between the ribbon and the silicon wafer. This mode of failure is identified by an increase in series resistance of the joint usually measured by electrical devices. The phenomenon is critical in modules which have weak interconnect bond strength due to poor soldering [9].

The improvement of the service lifetime of the ribbon in the PV module can be achieved through the use of materials that can withstand higher thermo-mechanical and fatigue stresses than existing copper ribbons. Material parameters to consider and control in the development of such material are coefficient of thermal expansion (CTE), mechanical properties (yield strength, elongation, Young's Modulus), a melting point of the solder and soldering temperature, as well as thickness and profile of the coating [25]. Also, the optimum geometry of ribbon for which elongation and contraction have minimal effect on its service lifetime should be developed and used in the PV module.

Failure of Busbar in PV Module Interconnect

Busbar consists of silver paste. It makes physical, thermal and electrical contact with silicon. When electricity is generated in the silicon wafer, it passes through the busbar which delivers it to the ribbon via the solder joint. Owing to differences in CTE of busbar, silicon wafer, and solder, the continuous bonding of busbar in the interconnection is an issue when the module has operated for a long time. Thermal resistance is created during soldering if the busbar is not flat or smooth. At higher soldering temperature silver dissolves in the busbar which accelerates module degradation [3]. A failure mode due to high edges and non-uniformity busbar topology is presented in Figure. 8.

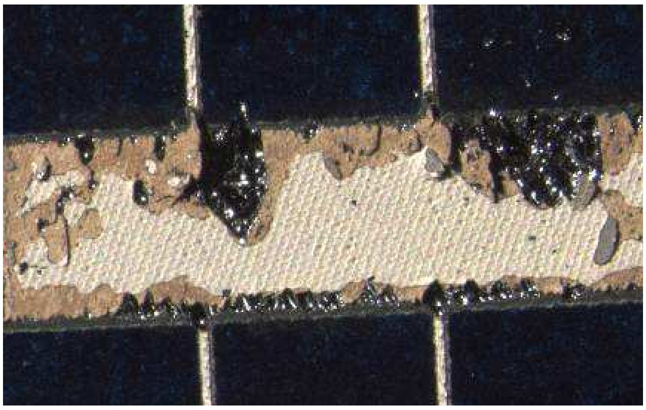

Figure 8: Failure Mode Due to High Edges and Non-Uniformity Busbar Topology [3]

Module degradation is also accelerated by residual stress developed in the busbar paste during firing process[26]. It is found that busbar performance and its thermo-mechanical reliability can be improved by determining and using suitable busbar topology as well as optimizing the minimum amount of silver paste used for the busbar [3]. Improving the formulation and chemistry of busbar paste has the potential of enhancing its strength and improving its response to residual stress and thus provide good adhesion [26].

Failure of Other Module Components

The failure of the semiconductor device and packaging materials are considered in this section.

Semiconductor Device

Crystalline silicon is used to make semiconductor device in crystalline PV modules. There are two types which are monocrystalline and multi-crystalline solar cells. The main difference between them is the crystal structure of the silicon wafer used in making the cell. As their names imply, monocrystalline silicon is made of single crystal silicon while multi-crystalline silicon is made of multiple crystals silicon. The monocrystalline and multi-crystalline silicon is produced in wafer form and then processed into solar cells. Though monocrystalline silicon solar cells perform better than their multi-crystalline counterpart, their mechanical and electrical properties are similar. Under the same thermo-mechanical loading, there is no significant difference in their behavior. Degradation of crystalline silicon solar cell is an observed failure mechanism [7] which evolved from cell cracking. During soldering and fabrication, cells experience strain from which micro-cracks develop and propagate across the cross-section. As silicon wafers are made thinner, reliability concern increases [27, 28] because the thinner the wafer, the more susceptible it becomes to crack initiation and propagation. Presented in Figure. 9 is an image of a PV module with cracked cells. The cells will not be efficient in power generation due to the cracks and this will impact on its power output during field operations. To reduce the tendency of cells to crack, consideration should be given to its manufacturing processes. Spot soldering is a promising technology with the capability to limit damage to a small area. The process distributes the stresses over a larger area more evenly [28]. This technique will reduce the thermal load on the wafer as well as minimize the formation of micro-cracks.

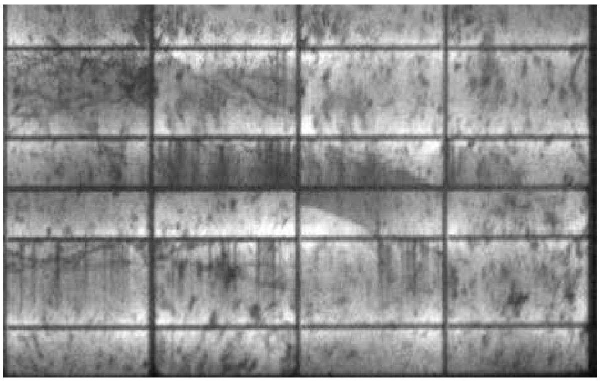

Figure 9: An Image of a PV Module with Cracked Cells [2]

Packaging Materials

Thermo-mechanical loading affects PV module packaging materials. The materials are used to laminate and support the solar cells assembly. These materials which include encapsulant, back sheet, and glass covering are shown in Figure. 10 for a typical packaging of crystalline silicon PV module.

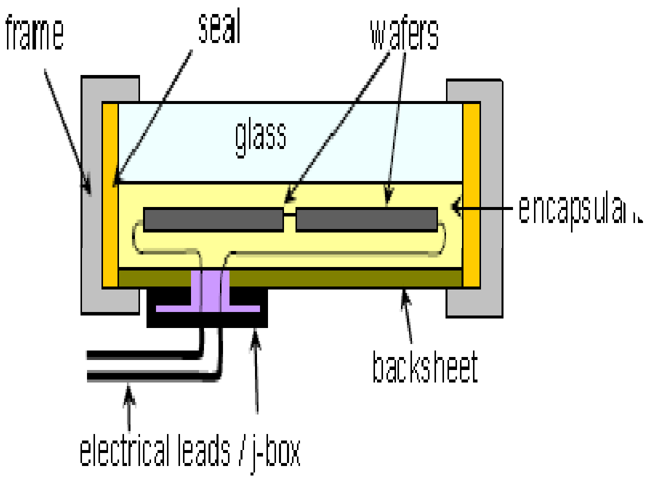

Figure 10: Typical Packaging of Crystalline Silicon PV Module [1]

An encapsulant is used to enclose the solar cells and interconnects as well as to affix the solar cells assembly to the cover glass and the back encapsulating material. They are also used to provide a shield to resist moisture and also electrical isolation. Under thermal exposure, the encapsulant undergoes accelerated degradation and aging. This occurrence changes the color of encapsulant and reduces module light efficiency and performance [7, 29]. EVA is one of the foremost encapsulants used in the manufacture of PV modules. Its long-term exposure to short-wavelength ultraviolet (UV) sunlight and the service operations of the module at temperatures near 50 □odule at temperatures nration such that it becomes ‘‘brownish’’ or ‘‘yellowish’’.King et al [32] reported that specific prominence has been given by researchers and manufacturers to reduce the discoloration effect caused by thermal exposure. It is also necessary that manufacturers of poor quality EVA improve and adequately test their formulations to ensure it remains as transparent as possible and with high durability throughout the service life of the PV module [29].

Delamination is another challenge experienced by PV modules during service operations mostly in hot and humid climates. Humidity in conjunction with heat enables the formation of water vapor which converts to moisture when the temperature reduces to an appropriate level. When moisture penetrates into the interface between the encapsulant and the front surface of the solar cells in the module, it weakens the interfacial adhesive bond resulting in their separation. The effects of delamination include increased numbers of ingress paths for moisture accumulation, performance loss due to the optical separation of the encapsulant from the cell and corrosion of metallic contacts such as solder joints [32]. The combination of these effects on PV modules results in substantial losses in performance. During manufacturing, proper lamination of all components enclosed in the module is vital to avoid moisture penetration and ensure the proper functioning of the components.

The back sheet layer of a PV module provides support at the backside of the module as well as additional insulation and moisture protection for the laminated PV components. Under thermal cycling the back sheet layer is subjected to degradation stresses which cause aging thereby affecting its durability. The degradation can lead to back sheet cracking[30] and detaching due to weakened interface bonds. Cracked or detached back sheet provides access to moisture into the module encapsulated components. The result is usually module damage. Thus, it is essential that a highly durable back sheet is utilized in a PV module for improved reliability.

Glass is used as a cover plate and for transmitting visible solar radiation into the PV module. The glass used in modules has low iron content, is ultra-clear and has a high transmittance rate to extract as much solar energy from the sun as possible. It is made of tempered glass which had been through a rapid heating and cooling process to enhance its strength. Although the glass is strengthened, it still suffers a significant amount of breakage. Its breakage occurs during vandalism and handling. It can be broken by wind load, hailstones, snow slides, as well as thermal stress. Under thermal loading by solar radiation, the glass can absorb a large amount of invisible solar infrared energy and incur significant tensile stress which can ultimately result in fracture and breakage [31]. In order to ensure more durability and reliability, the glass could be designed to withstand higher thermal loading. Adequate care should be taken during the tempering heat treatment process and heat strengthening to avoid small inclusions in float glass which can cause glass breakage.

ANALYSIS AND DISCUSSIONS

This section comprises two sub-sections. In section 5.1, the general discussion on thermo-mechanical failures of PV modules is presented while attempts are made in analyzing the failures. In section 5.2, the authors present suggested paradigm and techniques to improve the reliability of solder joints in PV modules.

General Discussion on Thermo-Mechanical Failures

PV module components have varied thermo-mechanical failure rates. Kontges et al [35] investigated the failure rates of 2000 IEC 61215 certification projects for standard testing of PV modules from 2007 to 2012 and the results of the failure rate for each year are presented in Figure. 11. The figure shows that the highest failure rate is 30% and it occurred in the year 2008. It also shows that the lowest rate is 10% and it occurred in the years 2011 and 2012. The reduction in failure rate can be attributed to improvement in the quality of modules produced in the later years.

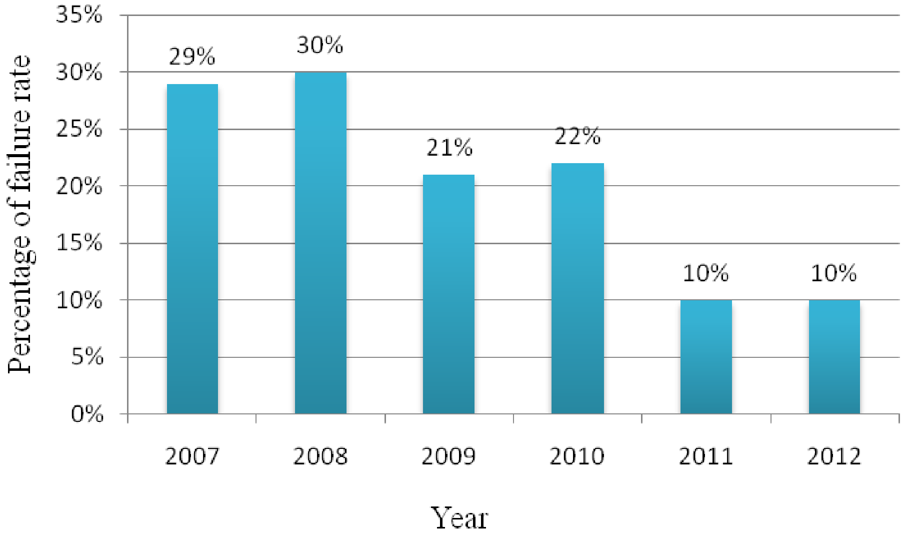

Figure 11: Failure Rates of 2000 Certification Projects for IEC 61215

Kontges et al [35] also investigated the distribution of failed tests vehicles of 1740 IEC projects and the information obtained is presented in Figure. 12. This figure shows that the highest PV module failure occurs at 200 cycles during the thermal cycling test which accounted for 18% of total failures. It can also be observed that for 50cyclesthermal cycling test, only 4% of the modules failed. This indicates that as the number of thermal cycling test increases, PV module failure rate increases. The main purpose of the thermal cycling test is to simulate thermal stresses on materials particularly solder interconnections inside the PV module laminate. Therefore, thermal cycling failures suggest failures of solder interconnections.

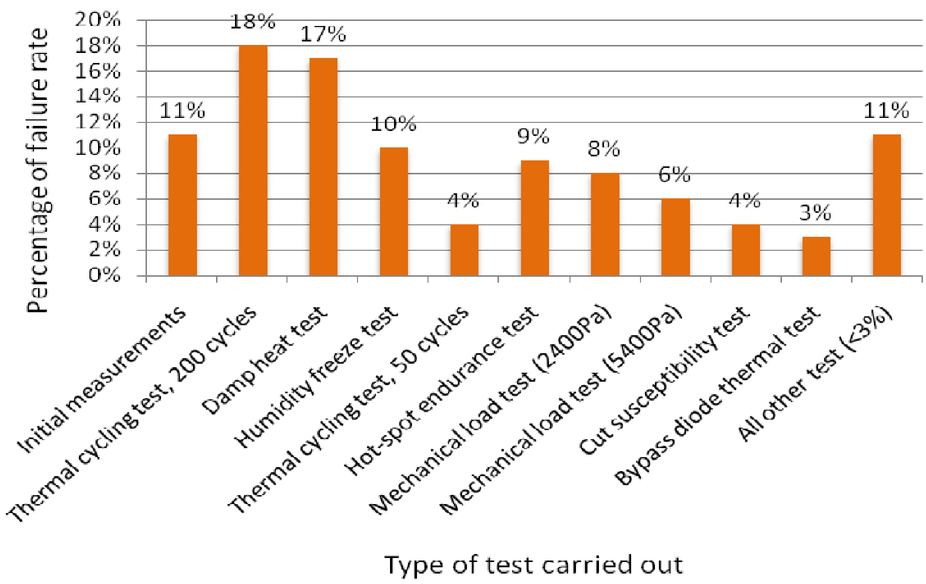

Figure 12: Distribution of Failed Tests of 1740 IEC Projects

The comparison of results of PV module certification tests and field failures observed provides evidence which further validates the certification tests. The result is represented as in figure. 13 which depicts types of PV module field failures observed in two separate investigations by Wohlgemuth [36] and DeGraaff et al [37], respectively. Wohlgemuth studied about 2,000,000 modules which failed between 1994 and 2005 while DeGraaff et al studied modules from 21 manufacturers which failed between 2003 and 2011. Figure 13 shows that in Wohlgemuth's study, the highest but one failure is 40.7%. This percentage consists of cell or interconnect break. In DeGraaff study, the highest failure was 36% comprising laminate and internal electrical circuit. Although the PV modules studied were produced by different manufacturers, the failure pattern is similar. Thus, it can be inferred from the results of thermal cycling tests as well as observations from field failures that solder joint failure is the most critical reliability issue of PV module assembly.

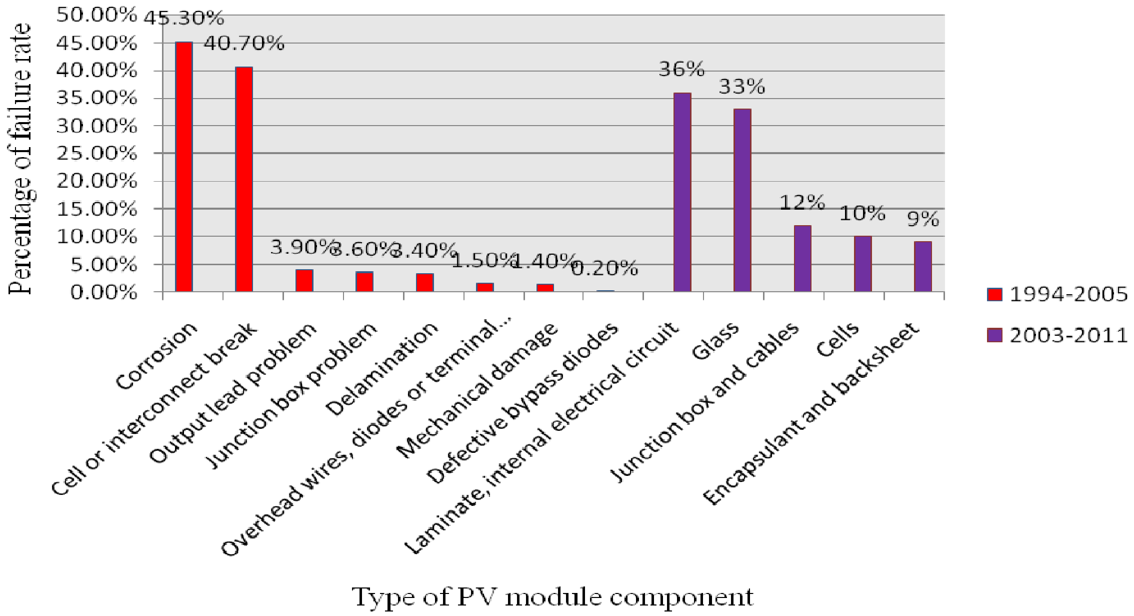

Figure 13: Types of PV Module Field Failures Observed

Proper understanding of solder joints failure in PV modules is necessary for the development of high integrity solder joints to ensure thermo-mechanical reliability in the module. King et al [31] reported that as a PV system ages, gradual increases in the cumulative series resistance result in power output declining to a median rate of 0.5 %/yr in monocrystalline silicon modules. They further reported the use of thermal infrared imaging to identify locations in the modules which have unusually high series resistance. Thus, solder joints are identified as a definite source of increased series resistance in some field-age modules. Further, microscopic investigation of solder joints cross sections provides a better understanding of impacts of both thermal fatigue and manufacturing processes on solder joints integrity. As solder joints become aged due to continuous thermal cycling during modules field operations, expansion and contraction cause solder fatigue. The joints become more brittle and the members disassociate from one another. These phenomena make the solder joints vulnerable to crack as they become more resistive with age. When thermal mismatches in solder joints are large, temperature changes increase mechanical stresses in the joints which eventually lead to fatigue failure.

Tarr [38] presented a relationship which could be used to compute thermal mismatch in solder joints. This relationship is presented in Eq. (1):

$\Delta U = \Delta e \times L \times \Delta T$ (1)

Where: ΔU is thermal mismatch ppm.m,

Δe is the difference in CTE between materials in ppm/^oC,

- L is the longest dimension of the component (often the diagonal) in m,
- ΔT is the temperature change in ^oC.

To illustrate the effect of thermal mismatch in solder joint, consider 95.5Sn/3.8Ag/0.7Cu with a CTE of 23.2 ppm/^oC bonded to a copper ribbon with a CTE of 17 ppm/^oC as presented in Table 1. If the longest dimension of the solder joint in a PV module is 0.15003m and temperature changes are 10, 20, 30, 40, 50, and 60^oC, then the thermal mismatch for each temperature change can be computed using Eq. 1. The results obtained are plotted in Figure.14. The plot could be used to illustrate the effect of thermal mismatch in the solder joint. The figure shows that as temperature change increases, thermal mismatch in solder joint increases. The relationship between the two is linear.

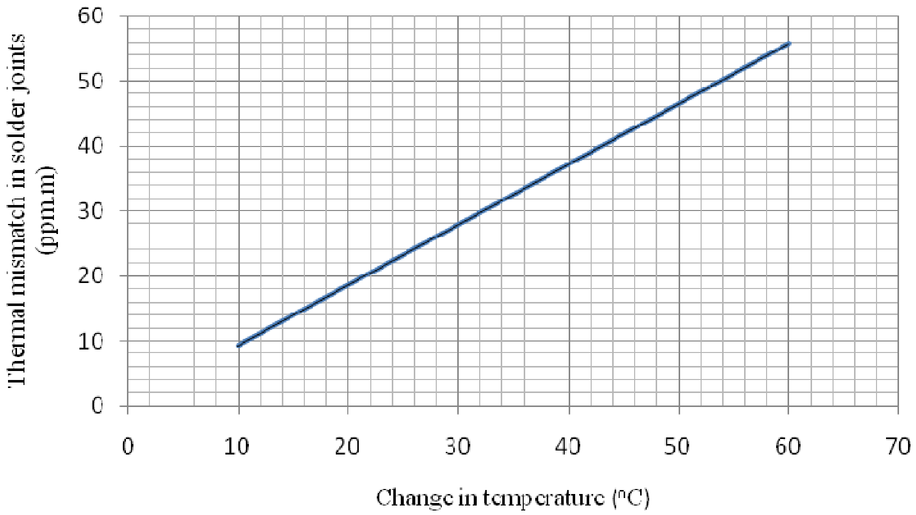

Figure 14: Effect of Thermal Mismatch in Solder Joint

To further understand the failure mode of solder joints in the PV module, a closer look at the failure mechanics is needed. It is well known that when Sn-Ag-Cu alloy solder is soldered to a substrate Cu pad, intermetallic (IMC) compounds are formed between the solder interface and Cu pad[39-41]. Similarly, in a PV module, IMCs are formed at the solder-copper ribbon interface during the soldering process for interconnection of solar cells. These IMCs play a crucial role in solder joint deformation where inhomogeneous and local strains develop at the interface. During the field service life of PV modules, the IMC continues to grow and increase in thickness [42]. When the IMC thickness reaches a critical threshold, failure of the solder joint occurs. In view of this, it is crucial that the presence and growth of IMC are taken into consideration in designing high integrity PV module.

Suggested Paradigms and Techniques to Improve the Reliability of Solder Joints in PV Modules

The authors propose further study on thermo-mechanical reliability of solder interconnections in PV modules which will include IMCs in the geometric model as shown in Figure. 15. Analysis of the effects of IMCs will provide insight into the degradation of the solder joint. This will facilitate a robust design of the joint for a longer lifespan.

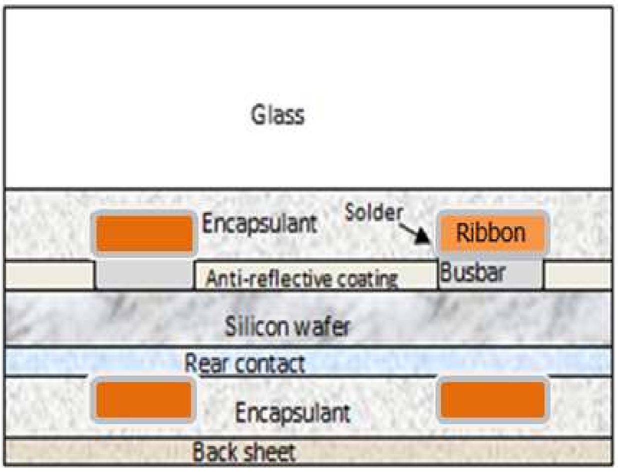

Figure 15

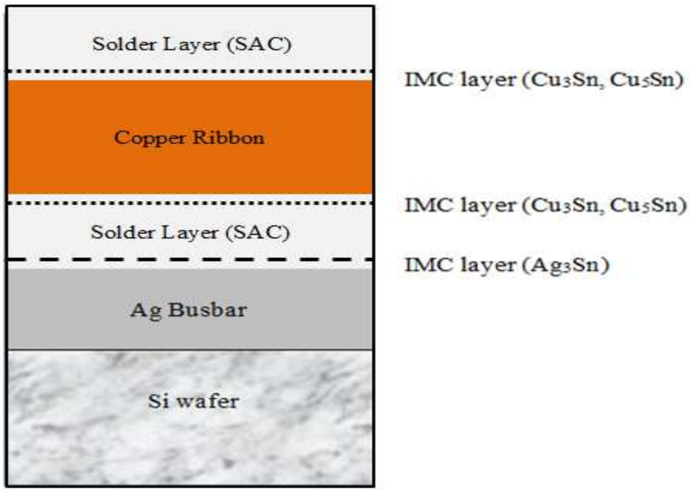

Figure 16

Furthermore, the authors are of the view that the optimization of the parameter settings of the solder joints involved in the manufacture of these modules will definitely improve the reliability of PV module assembly. In addition, Finite Element Modelling (FEM)can be employed in the early design stage of PV module solder interconnection because it has the potential to predict the response of the solder joint to cyclic thermo-mechanical stresses and strains. It could also be used to determine the contribution of the formation and presence of IMC to the reliability of solder joints. This will enable the determination of an optimal parameter setting of the solder joint to improve the thermo-mechanical reliability of PV module assembly.

CONCLUSIONS

This paper presented and discussed an assessment of failure modes of PV module subjected to thermo-mechanical loading. The evaluation extends to component failure mechanisms while dwelling on interconnect failure characteristics. Module interconnection consisting of solder joints, ribbon, and busbar is found to be the most vulnerable part to degradation and failure. Evaluation analysis reveals that differences in CTE among these bonded materials and long repeated temperature cycling 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.

An evaluation of failures from the thermal cycling tests and that observed from field test vehicles shows that solder interconnection failures are the most prevalent compared with failures of other components in PV module assembly. It was also found that solder joint failure is the most critical of interconnection failure. Its failure results in non-delivery of any generated electricity in the module because of electrical discontinuity with the ribbon strip. Further analysis of solder joint failure mode revealed that the formation and growth of IMC at the copper/solder interface affect solder joint reliability. The authors propose that the presence of IMC should be taken into consideration during design and analysis of the response of solder joint in the PV module to environmental thermo-mechanical loads. The practice will facilitate the manufacture of high integrity solder joints in the PV module assembly for improved module operational reliability as well as increased lifespan.

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