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EFFECT OF INTERMETALLIC COMPOUNDS ON THERMO-MECHANICAL RELIABILITY OF LEAD-FREE SOLDER JOINTS IN SOLAR CELL ASSEMBLY

M. T. ZARMAI, N. N. EKERE, C. F. ODUOZA & E. H. AMALU

School of Engineering, Faculty of Science and Engineering, University of Wolverhampton,
Wolverhampton, WV1 1LY, UK

ABSTRACT

The solder joints in crystalline silicon solar cell assembly undergo thermo-mechanical degradation during the device lifetime. The degradation is accelerated by the formation and growth of intermetallic compound, IMC, in a solder joint which contains copper and tin as alloying elements of the solder. This investigation quantifies the contribution of the presence of IMC in the joints on the reliability of the assembly. The study employs finite element modelling (FEM) to simulate the nonlinear deformation of SnAgCu solder joints in two models of crystalline silicon solar cell assembly. One of the models contains IMC in the interface joints between solder and copper ribbon while the other, which is the control, does not contain IMC in the joints. The degradation of the solder material is simulated using Garofalo-Arrhenius creep model. The geometric models were subjected to accelerated thermal cycling utilising IEC 61215 standard for photovoltaic panels. Analysis of the results of the creep strain profiles of the two models indicate that the deformation amplitude in the solder joint containing IMC is higher than that in the solder joint containing solder only. Similarly, it can be observed from the plot of strain energy density against load step that the solder joint containing solder+IMC have considerable higher strain energy density compared to solder only joint. This infers that the presence of IMC significantly impacts the thermo-mechanical reliability of the assembly joints. The results also demonstrate that IMC decreases the mean-time-to failure (MTTF) of the assembly joints.

KEYWORDS: Crystalline Silicon Solar Cells, Solder Joints, Reliability, Intermetallic Compound, Fatigue Failures

INTRODUCTION

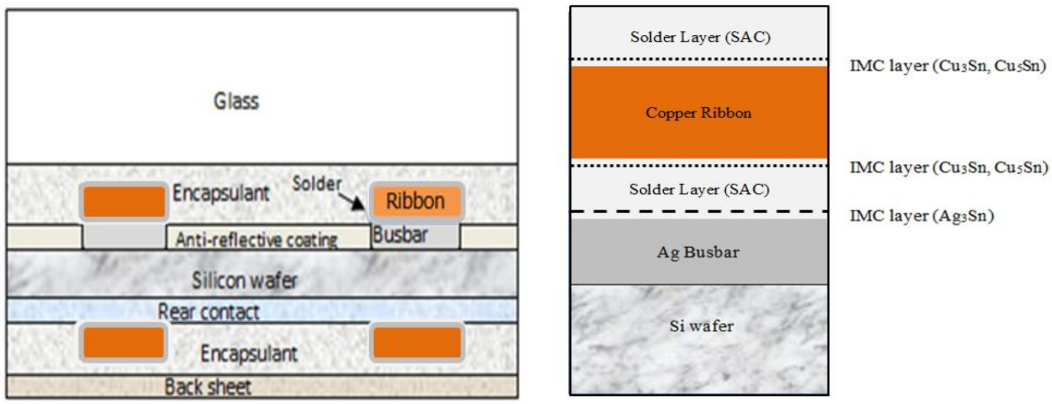
Wafer-based crystalline silicon solar cells are the most common and widely used solar cells with a production history of over 60 years. The global capacity for production of crystalline solar cells is high. Moreover, crystalline silicon solar cells deliver the highest efficiencies of energy conversion. Silicon is the primary feedstock used in the fabrication of crystalline silicon wafers for use in making solar cells. Solders are employed as interconnection materials for soldering silicon wafer to copper ribbon strip in solar cell assemblies in order to form a photovoltaic (PV) module. The solder joints in the assembly act as mechanical support to hold the ribbon strip to the silicon wafer via silver bus-bar. They also function as thermal conduit for heat dissipation away from the silicon wafer as well as providing the critical electrical interconnection between the silicon wafer and the copper ribbon. In this study, 95.5Sn-3.8Ag-0.7Cu lead-free (Pb-free) solder alloy is used. When this solder is used in the soldering process for solar cells interconnection, intermetallic compounds (IMCs) are formed at the solder-copper ribbon interface. 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 the PV modules, the IMCs continue to form and increase in thickness. When the IMC thickness reaches a particular threshold, failure of the solder joint occurs. This indicates that the development and growth of IMC at the interface of solder and bond region affects the structural integrity of solder joints(Che & Pang, 2012).In addition, solder materials in solar cell assemblies are subjected to thermo-mechanical loads during accelerated thermal cycling tests as well as in service operation. The mismatch of coefficient of thermal expansion (CTE) of silicon wafer, silver bus-bar, solder, copper ribbon strip and other components, leads to thermo-mechanical induced non-linear deformation in the solar cell assembly. The induced deformations in the solar cell assembly cause the solder materials to develop cyclic inelastic plastic and creep strains which cause cumulative fatigue damage resulting in failure of the solder joints(Pang, 2012; Hund & Burchett, 1991).This occurs when the cyclic strain increases to a particular high value and the ensuing damage in the solder material cause fatigue cracking in the solder joints thereby resulting in premature failure of the PV module's functional life (Hund & Burchett, 1991). Creep of a solder material is often characterized by its steady state creep strain rate (Pang, 2012).According to Che and Pang (2014), the steady state creep model of solder is of major concern due to its contribution to total creep deformation. Therefore, an investigation of steady state creep for non-linear deformation of SnAgCu solder joints in crystalline silicon solar cell assembly is needed to obtain more understanding of the degradation of solder material.

This study employs finite element modelling (FEM) to simulate the nonlinear deformation of SnAgCu solder joints in two models of crystalline silicon solar cell assembly. One of the models contains IMC in the interface joints between solder and copper ribbon while the other, which is the control, does not contain IMC in the joints. The Garofalo-Arrhenius steady state creep constitutive model for SnAgCu solder will be used in this study to simulate the degradation of solder material.

SOLAR CELL ASSEMBLY AND RELIABILITY

Architecture of Solar Cell Assembly

The manufacturing process of conventional wafer-based crystalline solar cells begins with the use of silicon wafer as a base. A layer of emitter material is deposited on this base on which a layer of an anti-reflection coating (ARC) is in turn deposited on. The ARC layer ensures passage of all light to the silicon crystalline layers while minimizing reflection. A transparent adhesive is deposited on the overlaid coating. Two layers of silver in grid form are then printed on the cell's semiconductor material such that the metallization penetrates the ARC layer and makes contact with silicon wafer to form the front metal contact and collect electric current generated. The printed contacts are fired. Typically, aluminium contacts are also printed at the back surfaces of the cell material. A typical Schematic of cross-section of a laminated crystalline Si solar cell is depicted in Figure 1 and consists basically of material layers including inter-metallic compounds. As can be observed from the figure, a rear contact material supports silicon wafer. The silicon wafer serves as a semiconductor consisting of a P-type layer at the rear and an N-type layer on the front. This layer is secured by a protective glass cover (Dirjish, 2012). Solar cells are interconnected with other cells in series and parallel to form a PV module of the required voltage and current. Presented in Figure 2 is a schematic of crystalline silicon solar cells interconnected in series with tabbing ribbon. However, it should be noted that the coefficient of thermal expansion (CTE) of the copper ribbon, solder alloy and silver bus-bar are different. The CTE mismatch induce thermo-mechanical stresses in the solder joint during soldering as well as service operations resulting in fatigue and eventual failure. It is desirable that the packaging of the PV module should ensure the solder joint maintains integrity and reliability through subsequent manufacturing processes as well as during service conditions.



(a) **(b)**

Figure 1: Schematic of Cross-Section of Typical Crystalline Si Solar Cell Assembly Showing: (a) Encapsulated Solar Cell Assembly (b) Soldered Interconnects Including IMC Layers

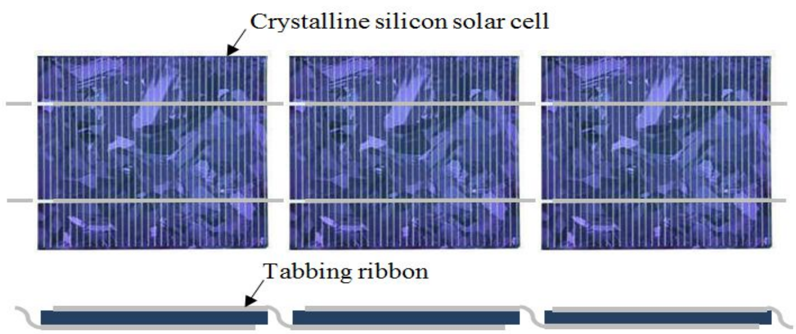


Figure 2: Crystalline Silicon Solar Cellsinter Connected in Series with Tabbing Ribbon

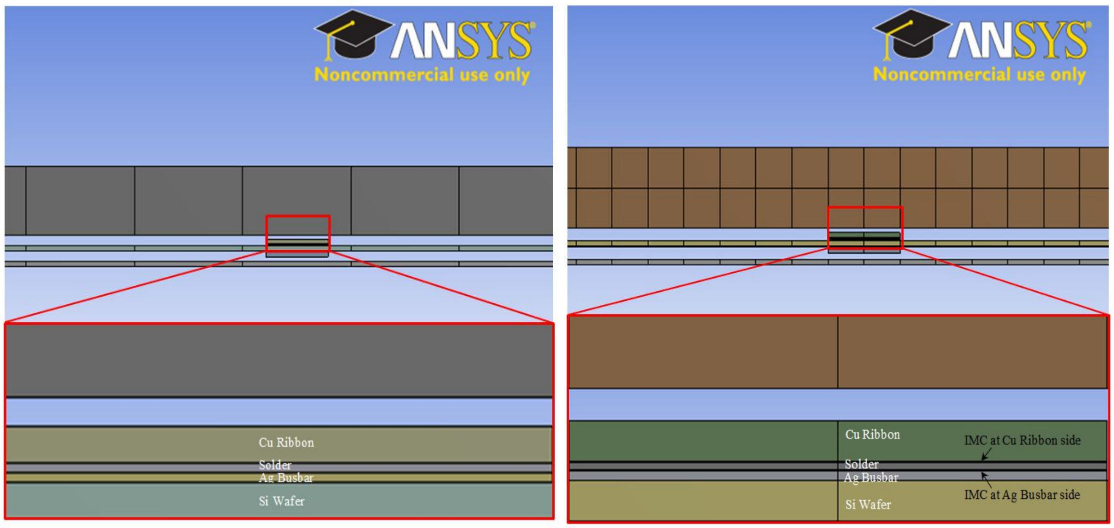
Solder Joint Reliability

In order to interconnect solar cells, printed contacts at the front and back surfaces of the cells are soldered to highly conductive copper ribbon strips for current transfer from the front of one cell to the back of a neighbouring cell in a series connection (Jeong et al, 2011) as shown in Figure 2. The reliability of solder joints can be affected by a variety of application conditions such as vibration, mechanical shock, thermo-mechanical fatigue, thermal aging and humidity (Lechovic et al, 2009). McCluskey (2010) and Cuddalorepatta et al (2010)reported that the soldered interconnect joint is the most susceptible part of the assembly. Moreover, in a BP Solar study of PV module field failures, Wohlgemuth (2008)reported that cell/interconnect break accounted for 40.7% of all types of field failures observed. The substantial failure of interconnects demonstrate their criticality and the need to provide urgent solution to this challenge. This study is focussed on the thermo-mechanical reliability of solder joints in crystalline silicon PV modules.

FINITE ELEMENT MODELLING AND SIMULATION

Background and Methodology

This study utilized 156 x 156 mm^2 multi-crystalline silicon solar cell assembly.The study of induced strain in solar cell assembly was carried out using commercial ANSYS academic research finite element package. Due to the magnitude of computations involved, the High Performance Computation (HPC) was executed using a Bespoke Work Station computer in the School of Engineering, University of Wolverhampton, UK.In order to lessen modelling time and disc space, quarter symmetry of the geometric models were simulated. Presented in Figure 3 are the meshed geometric models of the solar cell assembly with interconnected components for solder only (Figure 3a) andsolder+IMC(Figure 3b). The IMC layer thickness is 2 µm at each of the interfaces in Figure 3(b).



(a) (b)

Figure 3: Meshed Crystalline Si Solar Cell Assembly Showing Interconnected Components: (a) Model with Solder Only (b) Model with Solder+IMC

Materials and their Properties

The solar cell schematic cross-section presented in Figure 1 shows that the solar cell assembly consists of various materials with dissimilar properties. The materials include Sn-3.8Ag-0.7Cu solder, Cu ribbon, Ag bus-bar, IMCs and Si wafer. These materials and their corresponding properties were assigned to the geometric models built for this study. The properties of these materials such as Young's modulus, CTE, Poisson ratio and shear modulus were used.

Constitutive Solder Model

Solder joints in solar cell assemblies undergo thermo-mechanical loading during accelerated thermal cycling tests as well as in field service. The solder is assumed to exhibit elastic, bilinear kinematic hardening after yield. The elastic and inelastic deformation behaviour of the solder alloy is described by constitutive models. In this study, the Garofalo-Arrhenius hyperbolic sine creep equation was used to simulate the creep behaviour of Sn-3.8Ag-0.7Cu solder joints. This equation in the required format of input for implicit Garofalo-Arrhenius creep model is given by (Syed, 2004):

$$\dot{\varepsilon}_{cr} = C_1[sinh(C_2\sigma)]^{C_3} exp^{-C_4/T} \qquad (1)$$

The constants C_1, C_2, C_3 and C_4 for Sn-3.8Ag-0.7Cu solder are given in the Table 1.

Table 1: Generalized Garofalo Creep Constant (Syed, 2004

	Constant			
	C_1	C_2	C_3	C_4
Units	1/sec	1/Pa	-	K
Value	2.78E+05	2.45E-08	6.41	6500

Loads and Boundary Conditions

The IEC 61215 standard for testing photovoltaic panels was utilized to simulate thermal stresses on the materials of the geometric models. The models were subjected to six accelerated thermal cycling in 25 load steps between -40 ^oC to 85 ^oC. The temperature loading started from 25 ^oC, ramped up at a rate of 3 ^oC/min to 85 ^oC, where it had hot dwell for 20 min. It was then ramped down to -40 ^oC at a rate of 6 ^oC/min, where it had cold dwell for 20 min. The thermal cycling profile is presented in Figure 4 and it was used to accurately simulate actual cycling profile used during thermal load test.

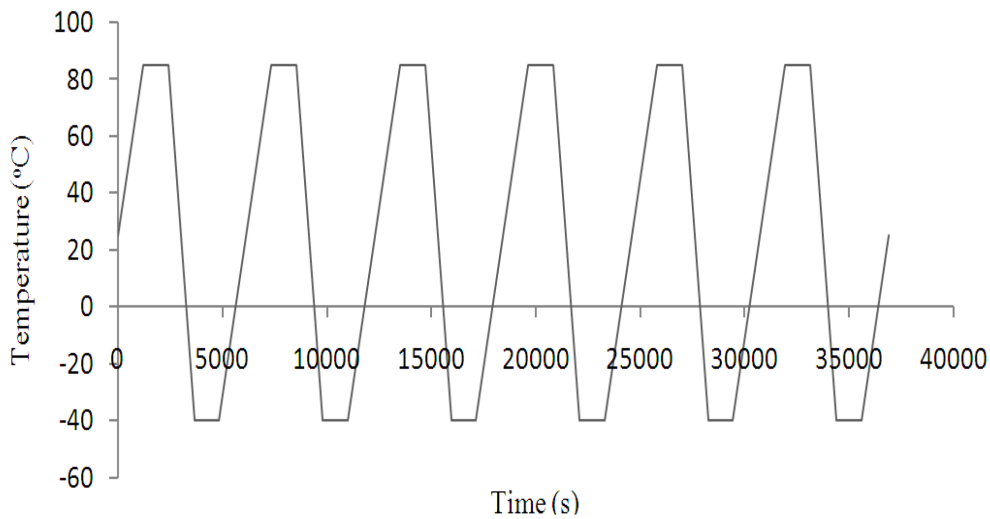


Figure 4: Plot of Temperature Profile of Thermal Load Test Condition Used in the Solar Cell Assembly

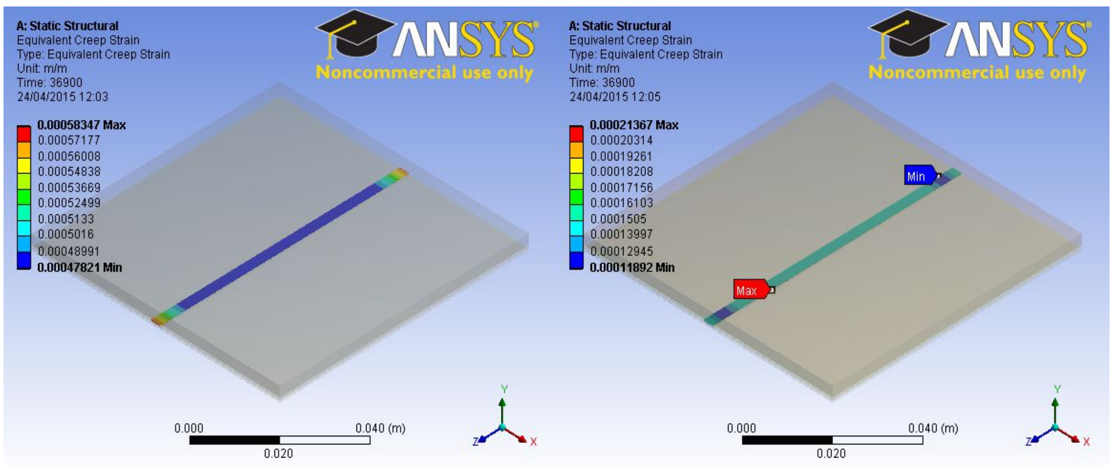
RESULTS AND DISCUSSION

Studyon Equivalent Creep Strain

Accelerated thermal cycling of solar cell assembly induces creep strain in the solder joints. The results of simulation are presented in Figure 5 which shows damage distribution of creep strain on the solder joints for both the model without IMC (Figure 5a) and the model with IMC (Figure 5b). In Figure 5(a)it can be observed that the greatest damage is at the two ends of the solder joint while in Figure 5(b) showing solder joint composed of solder+IMC, the damage is along the longitudinal section of the solder joint in addition to the damage at the ends of the joint. These damage regions indicate critical areas of the solder interconnection.

Presented in Figure 6 is a plot of equivalent creep strain on solder joint against load step. The plot shows that the solder joint in the model with solder only and that of the model with IMC experience creep strain deformation. However, there is difference in magnitude of deformation in the two models. Likewise, there is a substantial difference in creep strain response in the two solder joint compositions. The solder joint containing solder only experienced a sharp increase in creep strain at the first temperature ramp up followed by a decrease downwards as the temperature was ramped downwards. This trend of creep strain response continued in the pattern of thermal cycling profile. In addition, it can be observed that the creep strain gradually increased from a minimum value at the beginning of the first thermal cycling to a maximum at the end of the sixth thermal cycling. Conversely, the solder joint containing IMC appears to have strain hardened from the onset of thermal loading and stabilised through stress relaxation with fairly constant homogenous amplitude of deformation throughout the thermal cycles. The comparison of creep strain profiles of the two models indicate that the deformation amplitude in the solder joint containing IMC is higher than that in the solder joint containing solder only.

This indicates that the presence of IMC in the model enables predominance of fatigue failure mechanism than in the model without IMC.



(a) (b)

Figure 5: Creepstrain Damage Distribution Showing: (a) Creep Strain on Solder Only (b) Creep Strain on Solder+IMC

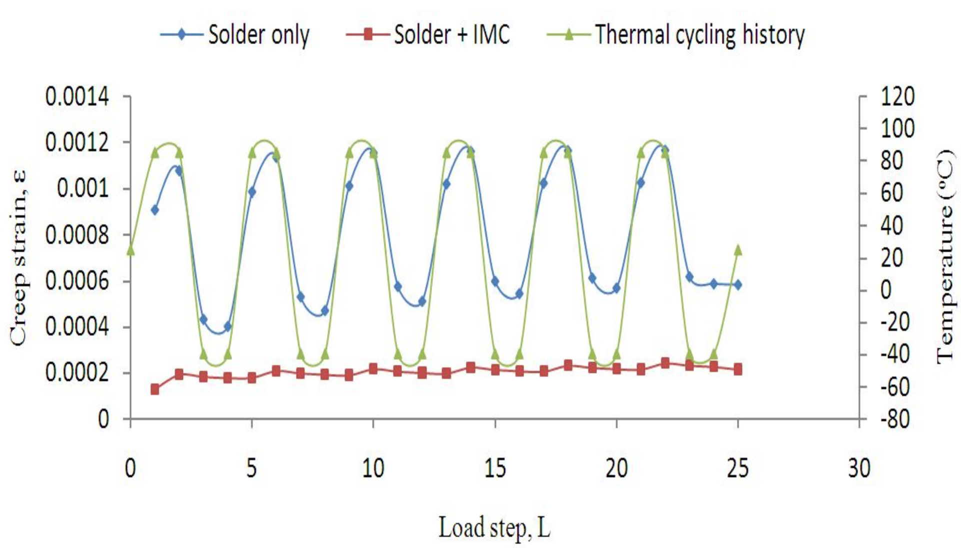


Figure 6: Plot of Equivalent Creep Strain on Solder Joint against Load Step

Studyon Creep Strain Energy Density

The thermal loading on the solar cell solder joint induces creep deformation in the joint. The deformation is stored internally throughout the volume of the joint as creep energy. Creep strain energy per unit volume of material is referred to as creep strain energy density. The plots of strain energy density against load step for both the model with solder only and that with solder+IMC are presented in Figure 7. It can be observed from the plot that the solder joint containing solder+IMC have considerable higher strain energy density compared to solder only joint. This infers that the presence of IMC in the solder joint significantly imparts the joint. Thus, the solder joint with solder+IMC is more susceptible to fatigue failure than the joint with solder only.

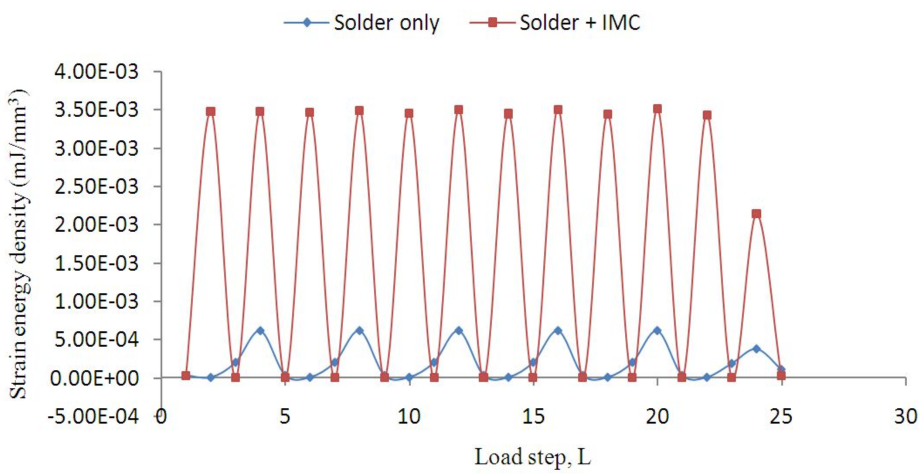


Figure 7: Plot of Strain Energy Density against Load Step

Effect of IMC on Assembly Solder Joint Fatigue Life Prediction

The fatigue life of solder subjected to thermal cycling is evaluated using the inelastic response of solder. Creep is considered as the primary damage mechanism for SnAgCu solder during thermal cycling and is solely used to simulate the material behaviour(Syed, 2004). The accumulated creep strain energy density per cycle is used to predict fatigue life of solder joints subjected to thermal cycling loading.The number of cycles to failure is given by(Syed, 2004):

$$N_f = (W' w_{acc})^{-1} \qquad (2)$$

Where, $N_f$is Number of repetitions or cycles to failure, W' is Creep energy density for failure and$w_{acc}$is accumulated creep energy density per cycle. The value of accumulated creep energy density per cycle in a solder joint is calculated and used to determine the number of cycles to failure. The constant W' have been determined experimentally to be 0.0019(Syed, 2004).

The fatigue life is also referred to as mean-time-to-failure (MTTF) or cycles to failure. In order to compute the fatigue life of solder joint, the values of accumulated strain energy density obtained from simulation of the models are inputted into Eq. 2. The computed value obtained for cycles to failure indicates the predicted fatigue life of the solder joint.

Presented in Table 2 is predicted solar cell solder joint thermal fatigue life. The table shows that accumulated creep strain energy density for solder joint containing solder+IMC is higher than that of the joint containing solder only.

Moreover, the predicted thermal fatigue life or cycles to failure of solder joint with solder+IMC is 26961 which is shorter than that of 182726 for the joint with solder only.This is a percentage change from solder only joint of 85%.

Table 2: Predicted Solar Cell Solder Joint Fatigue Life

Model	W'	w_{acc}	Predicted Life (Cycles)	% Change From Solder Only Joint
Solder only	0.0019	0.00288	182726	0
Solder+IMC	0.0019	0.01952	26961	85

CONCLUSIONS

The study of the effect of intermetallic compound on thermo-mechanical reliability of lead-free solder joints in multi-crystalline silicon solar cells using finite element analysis is presented. The study shows that creep deformation gradient in the model of solder joint with IMC accumulates along the longitudinal section of the joint while for the solder only joint; the deformation gradient is at the two ends of the joint. This shows that the solder joint containing solder + IMC experiences greater induced non-linear deformation than the solder only joint.The deformation amplitude in the solder joint containing IMC is higher than that in the solder only joint. This indicatespredominance of fatigue failure mechanismin the model with IMC than in the model without IMC.Furthermore, the solder joint containing solder+IMC have considerable higher strain energy density compared to the joint with solder only. Moreover, the predicted thermal fatigue life or cycles to failure of solder joint with IMC is much shorter than that of the joint with solder only. This implies thatfatigue failure is dependent on solder joint compositionsuch that the presence of IMC in the solder joint significantly imparts the thermo-mechanical reliability of the solder joint.

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