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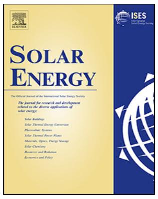

Investigation and analysis of thermo-mechanical degradation of fingers in a photovoltaic module under thermal cyclic stress conditions

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A R T I C L E I N F O

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A B S T R A C T

The reliability of current carrying fingers in a photovoltaic (PV) cell is essential to the overall performance of a PV module. The close proximity of the fingers to the solder layer makes it compelling to investigate its reliability under the premise of solder joint degradation, which is susceptible to high temperature transient variations. For the investigation of this particular aspect of finger reliability, a 3-D finite element model (FEM) of a PV module has been simulated under accelerated thermal cycle (TC) and outdoor weather temperature cycles. The FEM has been optimised to reduce computational complexity for accommodation of the small size of fingers in comparison to other components. Experimental TC test has also been performed on PV module batches to support the simulated findings by characterisation of observed finger breakages using illuminated current-voltage (I-V) and electroluminescence (EL) imaging technique. The finger-solder interface was identified to be vulnerable under prevailing thermal loading conditions, from both the simulated and experimental findings. To illustrate a larger spectrum of finger reliability, the influence of variable geometrical design parameters of finger and solder layer have been investigated for its dependence on electrical power loss and thermo-mechanical damage accumulation. It was demonstrated that solder thickness and finger spacing are key to the performance of fingers in a PV module. Under the outdoor weather temperature cycle the finger-solder interface was found to be more vulnerable to damage accumulation during the sunshine hours on a hot day as compared to a cold day. Further, an acceleration factor was estimated to establish a quantitative comparison between the outdoor weather temperature cycle and accelerated TC. This paper highlights the different aspects of thermo-mechanical degradation of fingers in PV modules under transient thermal conditions and is instrumental for optimization of variable design and packaging parameters for its enhanced reliability.

1. Introduction

A conventional crystalline photovoltaic (PV) module is a multilayered packaged structure having solar cells sandwiched between a glass and polymer backsheet with the help of an adhesive encapsulant. The cells in a module are assisted by a front grid of screen printed (generally) fingers and busbar for the current conduction process. A copper ribbon is soldered on top of the silver busbar to facilitate connection between different cells in the module. The solder layer in the metallization has the dual purpose of maintaining a low resistance electrical path between the ribbon and busbar, and also to provide a robust mechanical support. The packaged structure of the module protects the cell and its metallization against the external environmental conditions like transient temperature variations between the day and night. However, defects and degradation like ribbon and interconnect breakages, solder joint failures, and cell crack expansions are often observed, which reduce the reliability of its long term operation (Munoz et al., 2011; Ndiaye et al., 2013; Ndiaye et al., 2014). The solder layer has been identified to be particularly vulnerable to transient high temperature variations in the external environment (Ogbomo et al., 2018; Quintana et al., 2002) due to its creep property, which is a time-dependant strain plastic deformation at thermally stressed conditions (Ma, 2009; Shi et al., 2000). The fatigue accumulation in the solder joint ultimately leads to its breakage, which affects the bonding between the ribbon and busbar, this can result in increased series resistance and loss in power which eventually reduces the reliability of the operation of the entire PV module. Mechanical defects like finger breakages have also been reported to be observed under thermal stress conditions (Chaturvedi et al., 2013). The close proximity of fingers with the solder layer makes it compelling to identify its thermo-mechanical failure modes in the premise of solder joint fatigue degradation.

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For the purpose of thermo-mechanical fatigue analyses, the modelling of creep deformation in solder joints has been widely reported as it remains an essential part in all types of electronic components (Amalu and Ekere, 2016; Bosco et al., 2012). Similarly, this approach has also been utilized for assessing the degradation mode due to thermo-mechanical fatigue in solar cells of a PV module. Finite element model (FEM) is reported to be employed for estimation of thermo-mechanical fatigue response of the solder layer in a PV module (Amalu et al., 2018; Zarmai et al., 2017, 2016) since, the complex nature of the module makes it difficult to experimentally measure the internal stress, strain and creep material properties (Owen-bellini et al., 2017). The transient thermal loading used in these studies are dominantly standard thermal cycling (TC) test conditions as specified under the IEC 61215-Crystalline Silicon Terrestrial PV modules-Design qualification and Type Approval (IEC 61215 Standard, 2002). The accumulation of inelastic strain energy density per cycle obtained from FEM simulations has been used earlier as an indicator of the crack initiation and growth in the solder layer (Darveaux and Banerji, 1992). It has also been indicated that the fatigue crack can be influenced by fingers due to its close proximity to solder layer in the PV modules (Cuddalorepatta et al., 2010). But detailed work on fingers under thermal loading conditions has not been reported. It has not been considered in earlier reported model geometries due to its small size which increases the model complexity and therefore requires more computational resources (Bosco et al., 2016a). Also, different assumptions have been adopted in reported models like different levels of structural details, 2-D or 3-D representation, and the variation in material property used which affects the accuracy of the model (Syed, 2006).

The present study is channelled to address the void of information on the different aspects of thermo-mechanical behaviour analyses of fingers in PV modules. A 3-D FEM of a PV module has been utilised and simulated under accelerated thermal cycling and outdoor weather temperature conditions. The study is focussed on the finger-solder interface to discuss the behaviour of thermo-mechnical reliability of fingers. The information of the accumulated damage and principal stresses from the simulated FEM model is used as an indicator for damage accumulation. The TC test has also been conducted experimentally on PV modules and defect characterization has been performed using illuminated current-voltage (I-V) characteristics and electroluminescence (EL) imaging technique. The dependence of the damage accumulation in the finger-solder interface with certain variable geometrical design parameters has also been investigated. Additionally, the damage accumulation under outdoor weather temperature conditions has been simulated to compare the damage accumulated between a hot and cold day of the composite Gurgaon (India) climate. A quantitative comparison has been made between the outdoor and indoor accelerated TC conditions in terms of an acceleration factor.

2. Methodology

A three-dimensional (3-D) finite element model (FEM) of a generic PV module assembly was developed using COMSOL multi-physics software package. Since, the PV module is a multi-layered complex structure it has not been modelled in its actual dimensions, but a symmetric part with dimensions of 28 × 5.6 mm was simulated to reduce the computational complexity. The cross-sectional view of the geometry of the model is shown in Fig. 1. The top encapsulant layer has been made transparent in Fig. 1 to accommodate inside view of the module structure. The PV module assembly used in this study consists of a multi-crystalline silicon cell with front grid metallization's. The metallization consists of a screen printed silver grid of fingers and busbar. A tabbing copper ribbon is soldered on the top of the silver printed busbar. The metallized cells are sandwiched in a structure comprising of a front sheet of a glass and a layer of EVA (Ethylene-vinyl Acetate) encapsulant on both sides and a Tedlar backsheet. The glass cover is not included in the geometry to reduce the complexity of the simulation due to its high thickness in comparison to the other components of the module. A fixed constraint was applied on the top of the geometry to approximate its boundary condition. The material properties (Young's modulus, E; Poisson's ratio, n; Coefficient of thermal expansion, α) of the components used in the study are given in Table 1.

The solder alloy material used in the study is eutectic SnPb (tin-lead), nowadays some manufacturers have adapted to lead-free solder alloys because of the toxic nature of lead but still SnPb is present in most of the old installed modules. Its property has been modelled using the Garafalo-Arhenius hyperbolic sine relation which has been widely used by researchers to model the steady state creep response of solder material in devices (Amalu and Ekere, 2016; Shirley et al., 2008). The creep rate is described by the stress and temperature-dependent steady-state relation:

$$\dot{\varepsilon_s}(\sigma,\ T) = A \times [\sinh(C \times \sigma)]^n\, e^{-\left(\frac{Q_c}{RT}\right)} \tag{1}$$

where, $\dot{\varepsilon_s}$: Creep strain rate, A: Creep rate coefficient, C: Empirical constant, R: Universal gas constant, T: Temperature, σ: Reference stress, n: Stress exponent, Q_c: Creep activation energy.

The values of the constant for the eutectic SnPb (A = 1409 1/s, σ = 10 MPa, n = 2.7, Q_c = 53.5 kJ/mol) were taken from literature (Mukherjee et al., 2016). In this study, the effective creep strain at the interfaces and total creep dissipation in the solder layer obtained from FEM were chosen as the damage metrics. It has been termed as damage accumulation in further sections.

The simulations and experimental tests have been performed under accelerated thermal cycling and the outdoor weather temperature cycle conditions. The experimental tests were performed in an environmental chamber dedicated for the testing of PV modules under accelerated testing conditions. A standard thermal cycling profile designed using IEC 61215 was varied between −40 °C and 85 °C. The cycle began from 25 °C and was ramped down to −40 °C with a cold ramp rate of 1.67 °C/min, where it had cold dwell for 105 min. It was then ramped up to the 85 °C with a hot ramp rate of 1.67 °C/min, where it had a hot dwell period of 105 min, as shown in Fig. 2 (a). The data used for simulations was the outdoor weather temperature cycle was taken at National Institute of Solar Energy, Gurgaon in India. The temperature of the module was measured using thermocouples installed at the back-sheet of the module. The data used in this study is a 24 h data which was recorded every 10 mins. The simulations were performed for two extreme temperature days of the particular site; the hot (20th June) and cold day (1st January). The 24 h temperature–time profile for the hot and cold day has been shown in Fig. 2 (b).

The module samples chosen for the experimental TC testing were chosen from different manufacturers to be able to test different types of geometrical configurations. Crystalline silicon PV modules were divided into four batches (1 batch = 1 manufacturer) with two modules each were chosen for testing. All the modules had 36 cells connected in series with power between 30 and 40 W. The batches were characterised before and after the test using illuminated current-voltage (I-V) and electroluminescence (EL) imaging technique. The electrical parameters obtained from I-V measurements were maximum output power (P_{max}), series resistance (R_s), short circuit current (I_{sc}) and fill factor (FF) at standard testing conditions (1000 W/m^2, 25 °C, AM 1.5G) using a PV module I-V simulator. EL imaging technique was used to obtain spatially resolved information for isolation of defect type as I-V analysis provides only the global degradation information. EL imaging is a fast measurement characterisation technique, it detects and spatially maps the luminescence emission of minority carriers from a forward biased solar cell. The cell emits infrared radiation in the range of 1000 to 1200 nm at room temperature via radiative recombination of the minority carriers. The intensity of the EL emission matches with the minority carrier diffusion length in multi-crystalline materials (Fuyuki et al., 2007). The reduced minority carrier density regions can be spatially detected appearing as lower intensity regions or dark spots,