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Estimation of the degradation rate of multi-crystalline silicon photovoltaic module under thermal cycling stress

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ABSTRACT

The overall power of an outdoor-exposed photovoltaic (PV) module decreases as a result of thermal cycling (TC) stress, due to the formation of cracks between the solder and metal. In this study, the thermal fatigue life of solder (62Sn36Pb2Ag) interconnection between copper and silver metallization in PV module was studied. This paper describes in detail the degradation rate (R_D) prediction model of solder interconnection for crystalline PV module. The R_D prediction model is developed which based on published constitutive equations for solder and TC test results on actual PV module. The finite element method was employed to study the creep strain energy density of solder interconnections in TC conditions. Three types of accelerated tests were conducted to determine the prediction model parameters. R_D in benchmark condition is predicted and compared with those of TC conditions.

1. Introduction

Photovoltaic (PV) modules that are continuously exposed to direct sunlight in day-and-night cycles tend to experience a thermal load because of the mismatch between the coefficient of thermal expansion (CTE) of solder and silicon wafer. In other words, the time history of thermal cycle induces thermal stress to the solder interconnection.

Traditionally, the individual solar cells in a PV module are connected in series using flattened copper (Cu) wires dipped in molten solder material. The Cu wire is soldered to the silver (Ag) electrode on the face of the cell. The cyclic thermal stress leads to fatigue cracks at the solder interconnection [1], which in turn increases the series resistance (Rs) of a PV module. This results in an overall drop in the power generated by a PV module. The R_s of a PV module typically arises from the resistances in solder joints, emitter and base regions, cell metallization, and cell-interconnect bus-bars, and resistances in junction-box terminations [2]. The increase in the value of R_s reduces the voltage produced by the cell, which ultimately depreciates the performance of the PV module. Furthermore, the outdoor deployment of PV modules on a day-to-day basis increases thermal stress and results in a gradual increase in Rs. More quantitatively, Morita et al. [3] have demonstrated that the performance loss of outdoor-aged PV modules exceeds 10% due to an increase in R_s values caused by the cracks at the solder interconnections.

The lifetime of PV module is expected to be over 25 years. Typically, 90% of the initial power output is guaranteed for the first 10 years, while 80% of the initial power output is accepted for the first 25 years. However, predicting the fatigue life of solder interconnections has been one of the most difficult problems in the PV industry. Recently, Cuddalorepatta et al. [4] assessed and compared the durability of lead (Pb)-based and Pb-free PV modules. They have predicted the acceleration factor (AF) based on the physics of failure analysis, and have also showed that the crack occurred at the interface between the solder and the Ag electrode. Meanwhile, Wohlgemuth et al. [5] have performed the longer thermal cycling (TC) test to evaluate the ability of a PV module to withstand cyclic exposures to extreme temperature conditions, instead of the conventional cycles of International Electrotechnical Commission (IEC) 61215. According to their study, continued TC of PV modules resulted in a gradual degradation of output power for most modules.

The IEC 61215 test, especially the Section 10.11 "Thermal cycling test," defines the TC test to determine the ability of the module to withstand thermal mismatch and fatigue over the temperature range −40 to 85 °C for 200 cycles with less than 5% degradation. However, the TC based on IEC 61215 is not intended to be life test [6]. Therefore, the present study aims to predict the module degradation rate (R_D) under thermal fatigue condition using a combination of accelerated testing and simulation method. The

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outcome of this study is expected to allow prediction of the realistic lifetime of PV modules under various climatic conditions, and enable the computation of AFs for TC tests.

2. Experiment

In this study, PV modules containing 6-inch-long multi-crystalline silicon solar cells were used for the analysis. The typical characteristics of the cells at a light intensity of 1 sun were as follows: open-circuit voltage (V_{oc}), 0.60 V; short circuit current (I_{sc}), 33.9 mA/cm^2; fill factor (FF), 0.72; and conversion efficiency, 16.8%.

The cells were interconnected by using copper ribbon wire (0.15 mm × 1.5 mm) plated with 62Sn36Pb2Ag solder. The solar cells were laminated with low-iron glass of thickness 3.2 mm and length and width 180 mm, EVA sheet of thickness 0.35 mm and Tedlar/PET/Tedlar (TPT) back-sheets of thickness 0.35 mm, as shown in Fig. 1. The EVA lamination was performed by heating them up to 150 °C for 12 min. After encapsulation, the samples were divided into three groups and exposed to accelerated stresses, as shown in Table 1. ATs were carried out with each of the 10 samples. TC conditions were achieved in an environmental chamber (Excal 5425-T, Climats Co., Bordeaux, France). The temperature conditions mentioned in Table 1 were measured at the backside of PV module during the cycling and are not the chamber conditions. Fig. 2 shows that the benchmark profile, obtained from inhouse data [7], has a cycle time of 24 h: 23–67 °C; 390 min ramp up and 330 min ramp down; 2 h dwell in high temperature and 10 h in low temperature.

The electrical performance of each sample was measured every 200 cycles by using a solar simulation system (K202-Lab200, Mac Science, Seoul, South Korea). The standard test conditions maintained during the experiments were (a) irradiance, 1000 W/m^2; (b) cell temperature, 25 °C; and (c) spectral distribution of irradiance, AM 1.5G (IEC 60904-3). The cross-sectional view of the degradation sites was observed by using a scanning electron microscope (ESEM-FEG XL30, FEI, Eindhoven, Holland).

3. Results of accelerated test

Fig. 3(a) shows the changes in average normalized $P_{\max}$ of the modules plotted as a function of cycle. As can be seen from the figure, $P_{\max}$ decreases linearly over time. Several authors [8,9] argue that a linear R_D cannot be taken for granted due to the limited availability of experimental data. Rather, an exponential R_D could be a more suitable trend, as is the case in some optoelectronic devices. However, it should be noted that both the trends exhibit a very similar evolution during the first 10–15 years – if similar initial yearly degradation rates are assumed – and then the linear degradation rate is a more pessimistic estimate [10]. In order to avoid the complexity of the discussions, we will not be considering the exponential degradation rate in this study. The cumulative distribution functions are shown in Fig. 3(b). Likelihood ratio (LR) test statistic is performed by first obtaining the LR test statistic, T. If the true shape parameters are equal, then the distribution of T is approximately chi-square. If $T \leqslant x^2(\alpha;\ n-1)$, the shape parameter estimates do not differ statistically significantly at the $100\alpha\%$ level, however, If $T > x^2(\alpha;\ n-1)$, the shape parameter estimates differ statistically significantly at the $100\alpha\%$ level, Where, $x^2(\alpha;\ n-1)$ is the $100(\alpha)$ percentile of the chi-square distribution, α is the significance level. In Fig. 3, T (1.00), is less than the Chi-Square (1.02), the shape parameter, 0.198, the estimates did not differ statistically at the 60% significance level.

Changes in the I–V curves, as shown in Fig. 4, also imply the degradation of the PV module. The V_{oc} and I_{sc} values remained stable over time. However, the value of R_s increased with each set of conditions, compared to the initial value (0 cycle). The main impact of increase in R_s is to reduce FF, which is the function of electrical resistance in the PV modules [11]. Therefore, the decrease of $P_{\max}$ can be attributed to the decrease of FF, which was caused by the increase in R_s.

Furthermore, failure analysis was performed by identifying the failure site through cross-sectional SEM imaging. Figs. 5(a–c) show the cross-sectional SEM image of the thermal fatigue cracking failure. The observed failure mode was identified by the formation of crack between the solder and the silver or along the grain boundary of the solder.

4. FE modeling and simulation

Finite element (FE) analysis was conducted by employing ANSYS v.15.0 finite element software. The stress analysis is conducted using two dimensional, plane-strain, non-linear, viscoplastic FE models. In addition to using 2-D models of the architecture, symmetry of the module architecture is routinely utilized in FE analysis. In the current study, in-plane symmetry of the package is exploited to model only one half of the PV module, as shown in Fig. 6. The out-of-plane thickness of the various layers like copper wire, solder joint, and silicon scaled to mimic their relative widths in the actual 3-D geometry of the PV module. The various materials in the model are distinguished based on their material properties as shown Fig. 6(a). The figure also shows the FE mesh density utilized for the current study. Solder interconnection was meshed with plane 183 elements. The total number of nodes and elements of the model was 33349 and 10880, respectively.

The solder material is modeled using creep and temperature dependent properties. The model is then analyzed for three complete TCs, simulating the actual profile as much as possible. The output from this simulation includes the accumulated creep strain

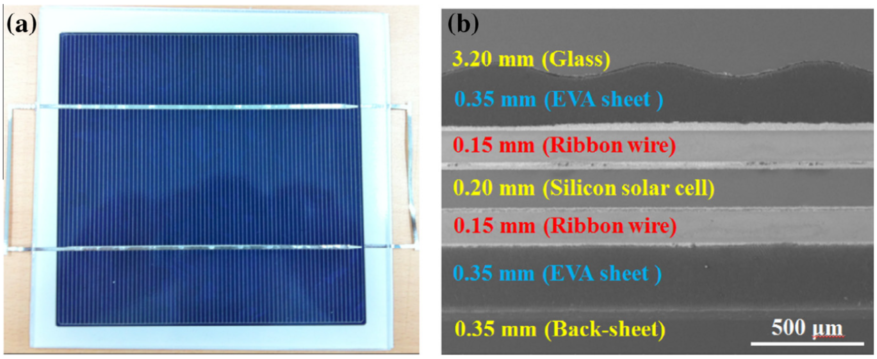

Fig. 1. PV module composed of multi-crystalline silicon solar cells of dimension 6-inches, used for the accelerated tests: (a) optical image, (b) cross-sectional SEM image showing the thickness of each layer.