Solder Bond Degradation of Fielded PV Modules: Climate Dependence of Intermetallic Compound Growth

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Solder Bond Degradation of Fielded PV Modules: Climate Dependence of Intermetallic Compound Growth

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Abstract — Solder bond degradation is typically ranked in the top two degradation modes observed in the field deployed modules. One of the main reasons for the solder bond degradation is the formation of intermetallic compounds (IMC) at the solder-cell metallization interfaces. The growth of IMC layer is dictated by the microclimate factors in which the modules are being exposed over several years. This paper presents the characterization and analysis of IMC layer of the modules, with identical model/type (Siemens M55), retrieved from two different field climates – Arizona (hot and dry) and Florida (hot and humid) along with an unexposed control module. The modules were tested with current-voltage (I-V), electroluminescence imaging and infrared thermography. The series resistance (Rₛ) and other electrical parameters of individual cells were obtained from dark I-V curves. The field induced degradation of Cu ribbon-solder and solder-Ag busbar interfaces were examined with scanning electron microscopy (SEM) imaging and energy dispersive X-ray spectroscopy (EDS) profiling. The IMC thickness is calculated, which exhibits a good correlation with cell Rₛ. Arizona modules operating at elevated operating temperatures suffered from thermomechanical fatigue, leading to the detachment of soldered ribbon from both top and rear cell contacts, while Florida modules showed higher degradation predominantly at the rear contacts due to the moisture transport and attack through the backsheet.

Index Terms — climate, intermetallic compound, IMC, PV module, SEM, series resistance, solder bond degradation.

I. INTRODUCTION

Reliability of field deployed photovoltaic (PV) modules is a great concern for PV stakeholders as it increases the financial risk. Exposure to the environmental stressors like UV light, heat, humidity, mechanical load and voltage bias etc. gives birth to variety of degradation and failure modes in the modules, which decrease their output power and lifetime. Many field studies showed that solder bond degradation is one of the top two degradation modes observed in the fielded modules [1], [2]. It is either caused by the individual or synergistic mechanisms of thermomechanical fatigue and intermetallic compound (IMC) formation [3]. During the soldering process, some of the metal substrate is dissolved into the molten solder to form a very thin and uniform layer of IMC at the metal–solder interface. The formation and growth of IMC at solder/substrate interface affect the reliability and lifetime of electronic joints. Itoh et al. elucidated two types of solder joint failures – Ag leaching into solder and long-term solder bond aging [4]. Ag leaching often leads to the cracks at Cu ribbon/Ag electrode interface. The crack inside solder joint is associated with large grain growing by repeated thermal stress and leads to contact degradation and power loss. Also, thermal cycling under regular operating conditions induce thermo-mechanical fatigue over these weak interfaces resulting in deterioration of metal contacts. It leads to increase in series resistance (Rₛ), which further cause the reduction of fill factor (FF) and maximum power (Pₘₙₚ).

Geipel et al. stated that the existence and growth of IMC within solder bonds influence the lifetime of interconnections as the solder joints turn brittle and become susceptible to fail under higher temperature cycles and humidity in the field [5]. It is reported that combination of humidity and temperature leads to more void formation at interconnects due to oxidation of Cu ribbon. The degree of intermixing of metallic interfaces and contact loss depend on climate conditions as temperature and humidity play a vital role in reaction kinetics of material degradation [6], [7]. Hence, understanding the failure mechanisms under different climate conditions can help improving the reliability of PV components. Further, quantifying the extent to which solder bond degradation and contact loss effects the series resistance is largely unclear.

The objective of this paper is to understand the influence of climate on solder bond degradation in the field-aged PV modules of same manufacturer through IMC thickness and to correlate it with cell I-V parameter.

II. METHODOLOGY

The study was carried out on one unexposed (control) and two field-aged modules of identical type. These modules have same glass/EVA mono c-Si cell/EVA/backsheet construction with standard solder type Sn60-Pb40. These modules were aged under two different climates of Arizona (AZ) and Florida (FL) for 18 and 10 years, respectively. Arizona has a hot and dry climate where the modules experience very high operating temperatures for most of the year, while Florida has a hot and humid climate with high moisture content in the air.
All the modules were tested with $I-V$ curve tracing, electroluminescence (EL) and infrared (IR) imaging to locate the regions with bad interconnect issues and their impact on electrical performance. The individual cells of each module were also accessed to obtain the electrical parameters though a set of light and dark $I-V$ curves. The cell $R_s$ was obtained from dark $I-V$ curve as it is more accurate and reliable method of parasitic resistance measurement. Based on EL and IR images, the most degraded cell in each module was selected for SEM and EDS destructive analysis. Three small rectangular pieces per cell were extracted from the busbar interconnect region to investigate different interfaces for IMCs. Individual cells of each module were extracted from a single cell. The epoxy set process starts by capsulating using epoxy set resin and hardener. Each capsule has three small rectangular pieces from the busbar interconnect region that reduces the %degradation. The change in shunt resistance was found to be significant. Another common degradation uncovered in both modules is encapsulant browning, which is distinctly visible by naked eyes. Significant browning of EVA is seen almost over entire cell area that reduces the transmission of incident photons to solar cells and hence loss in $I_{sc}$. Though AZ modules were sitting in the field for longer period as compared to FL modules, the major contributor of FF loss is considerable increase in $R_s$. The change in shunt resistance was found to be less significant. Another common degradation uncovered in both AZ and FL modules is encapsulant browning, which is distinctly visible by naked eyes. Significant browning of EVA is seen almost over entire cell area that reduces the transmission of incident photons to solar cells and hence loss in $I_{sc}$. Though AZ modules were sitting in the field for longer period as compared to FL modules, $I_{sc}$ degradation rate is greater in latter. It is because the browning reaction rate gets aggravated in the presence of humidity.

### III. Results and Discussion

#### A. Performance evaluation of field-aged modules

The module level $I-V$ parameters of unexposed and field-exposed modules are given in Table 1, along with the annual degradation rate. The %degradation is calculated with reference to unexposed (control) module. Since the length of field exposure is different in both modules, the module performance is compared while considering the degradation rate. It is observed that $P_{max}$ degradation rate is higher in FL module as compared to AZ module owing to greater FF loss and $I_{sc}$ loss to some extent. The major contributor of FF loss is considerable increase in $R_s$. The change in shunt resistance was found to be less significant. Another common degradation uncovered in both AZ and FL modules is encapsulant browning, which is distinctly visible by naked eyes. Significant browning of EVA is seen almost over entire cell area that reduces the transmission of incident photons to solar cells and hence loss in $I_{sc}$. Though AZ modules were sitting in the field for longer period as compared to FL modules, $I_{sc}$ degradation rate is greater in latter. It is because the browning reaction rate gets aggravated in the presence of humidity.

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**Fig. 1.** Process flow of sample preparation for SEM measurement, starting from the module cutting to inserting the test sample into the SEM instrument under vacuum.
TABLE I
I-V CHARACTERISTIC PARAMETERS OF TESTED MODULES. DEGRADATION RATE IS CALCULATED WHILE CONSIDERING UNEXPOSED MODULE’S DATA AND LENGTH OF FIELD EXPOSURE.

<table>
<thead>
<tr>
<th></th>
<th>$I_{sc}$ (A)</th>
<th>$V_{oc}$ (V)</th>
<th>FF (%)</th>
<th>$P_{max}$ (W)</th>
<th>$R_s$ (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unexposed</td>
<td>3.22</td>
<td>22.23</td>
<td>74.1</td>
<td>53.1</td>
<td>0.71</td>
</tr>
<tr>
<td>FL aged (10 years)</td>
<td>3.06</td>
<td>22.05</td>
<td>57.4</td>
<td>41.8</td>
<td>1.47</td>
</tr>
<tr>
<td>Deg rate (%/yr)</td>
<td>0.50</td>
<td>0.08</td>
<td>2.25</td>
<td>2.13</td>
<td>10.7</td>
</tr>
<tr>
<td>AZ aged (18 years)</td>
<td>3.02</td>
<td>21.84</td>
<td>63.8</td>
<td>42.2</td>
<td>1.52</td>
</tr>
<tr>
<td>Deg rate (%/yr)</td>
<td>0.35</td>
<td>0.10</td>
<td>0.77</td>
<td>1.14</td>
<td>6.30</td>
</tr>
</tbody>
</table>

B. Imaging of degraded solder bonds

Fig. 2 shows the EL and IR images of tested modules. Besides few finger defects, EL image of unexposed control module displays fairly uniform and bright luminescence emission with fewer defects. The IR image also showed very little variation in its thermal profile, indicating no critical issues in the module. On the other hand, EL images of the aged modules contain some inhomogeneous extra bright and dark regions that account to the module performance loss. The small pockets of bright EL spots correspond to poor solder joints, which is a resultant of shrinkage of interconnect cross-sectional area available for the electrons to pass through and leading to current crowding. The corresponding IR images relate these regions of higher temperatures above the average module temperature due to higher current density at interconnect interfaces. High temperature accelerates the IMC formation rate and increases the possibility of interconnect detachment due to reaction kinetics and CTE mismatch respectively. On comparison, FL module is appeared to be more degraded, which is corroborated by lower EL intensity and presence of more hotspots.

C. Microsection analysis of solder joints

Fig. 3(a)-(c) shows the SEM (top) and optical (bottom) images of cross-sectional area of cell-interconnect region. The SEM image of control module confirms a thin uniform contact between the Cu-solder and solder-Ag busbar. This also explains the low $R_s$ of the module. The EDS line scan, shown in Fig. 3(d) indicates very less intermixing of elements across the solder-metallization interface. During the pre-tinning and soldering process, copper core ribbon and Ag metallization are partially dissolved into the adjacent molten solder layer [8]. The diffusion of Cu and Ag atoms in the solder layer leads to IMC formation at two interfaces (refer Fig. 1). The overlap of elemental compositions at the interfaces follows nearly a normal distribution curve, out of which IMC thickness can be calculated using the full width half maximum (FWHM) method. The width at half the maximum height of bell curve allows the estimation of IMC thickness. The average thickness of Ag$_x$Sn$_y$ is 2.46 μm and Cu$_x$Sn$_y$ IMC is 1.66 μm for both front and back contacts.

The SEM image of a cross-section of FL module section clearly indicates that the solder joints are degraded severely at both sides. The deterioration of interfaces is attributed to prolonged aging period. The module experienced a greater number of thermal cycles at higher operating temperatures inducing greater thermomechanical fatigue that ruptures the interfaces. Only limited regions were available for IMC analysis. The average IMC thickness of Ag$_x$Sn$_y$ and Cu$_x$Sn$_y$ IMC is 4.15 μm and 2.54 μm respectively for both the contacts.

The SEM image of FL aged module showed the similar detachment of interconnects as in the previous case, but the degradation exists predominantly at bottom contact. The solder-Ag interface contains multiple voids, which are a result of increased weathering fatigue that deteriorates the interfacial strength. Interestingly, the rear contacts showed significantly
higher rates of detachment and IMC formation compared to the top contact. It is because that the combination of temperature and humidity creates more stressful environment leads to higher voids formation compared to isothermal heating. The bottom contact has thicker layers of Ag$_2$Sn$_y$ and Cu$_2$Sn$_y$ with the average thickness 6.50 µm and 2.66 µm respectively, against 4.39 µm Ag$_2$Sn$_y$ and 2.37 µm Cu$_2$Sn$_y$ for top contacts. This further consolidates of initial hypothesis that the moisture aggravates the degradation via IMC formation pathway.

![SEM and optical images](image)

Fig. 3. SEM (top) and optical (bottom) images of cross-sectional area of cell-interconnect harvested from a cell of (a) unexposed module, (b) FL aged module, and (c) AZ aged module. (d) EDS line scan across the region marked in (a), indicating the two bell curves of IMC layers enclosed in red boxes.

D. Correlation between series resistance and IMC thickness

Fig. 4 presents the correlation between cell Rs and thicknesses of Ag$_2$Sn$_y$ and Cu$_2$Sn$_y$ IMCs under different climates. The plot clearly illustrates a decreasing trend in cell level Rs with AZ field-aged being highest and unexposed being the lowest. This could be understood from the fact that AZ module was exposed to elevated temperatures for prolonged period of 18 years, while FZ module was 10-year old.

A direct relation is found between the IMC type and microclimate. The thickness of Ag$_2$Sn$_y$ IMC is found to be greater in FL module, which is favored by the moisture that causes the formation of metal oxides. In the case of Cu$_2$Sn$_y$ system, AZ module has thicker IMC since it is a diffusion-driven reaction. Since the diffusivity of Cu in Sn is three times higher than that of Ag in Sn, the high temperature of AZ accelerated the intermixing reaction.

![Graph](image)

Fig. 4. Variation of Rs and IMC thickness for unexposed and fielded modules from FL and AZ climates. The median value is indicated.

IV. CONCLUSIONS

The effects of solder bond degradation in two different climates (AZ and FL) on Rs increase was evaluated. A good correlation between Rs increase and solder bond fatigue through IMC growth and void formation was established in aged modules. SEM results demonstrated that solder-Ag interface in aged modules is uneven and degraded severely, while the unexposed module showed a thin and uniform IMC layer without any contact loss. The average thickness of Ag-Sn and Cu-Sn was calculated using FWHM method applied on the overlapping regions of elements between solder-Ag busbar and Cu ribbon-solder respectively. FL module showed thicker Ag$_2$Sn$_y$ layer IMC at rear contacts assisted by metal oxides formation in the presence of moisture. On the other hand, AZ module has thicker Cu$_2$Sn$_y$ due to higher diffusivity of Cu in Sn at high operating temperatures over longer exposure in the field.

This study is useful in understanding the underlying degradation mechanism for solder bond failures in PV modules installed at different climatic conditions.

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