Degradation of Solder Bonds in Field Aged PV Modules
Correlation with Series Resistance Increase

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Degradation of Solder Bonds in Field Aged PV Modules: Correlation with Series Resistance Increase

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Abstract - One of the major defects that can cause significant power loss is the degradation of interconnect metallization system (IMS) comprised of cell metallization and solder bonds of cell and string interconnects. Weak cell interconnect solder bonds between copper ribbon and busbar of cells result in series resistance increase which affects the fill factor causing a power drop. In this paper, the results obtained from series resistance and peel test experiments performed on the cells extracted from modules exposed in three different climates (Arizona - Hot and Dry, Mexico - Warm and Humid, and California - Temperate) for more than 18 years are presented. Finally, climate specific thermal modelling was performed for those sites over 20 years to calculate the accumulated thermal fatigue and to evaluate its correlation, if any, with series resistance.

Index Terms — series resistance, solder bonds, degradation, reliability, photovoltaic cells, silicon.

I. INTRODUCTION

One of the major reasons for power loss in the field exposed photovoltaic (PV) modules over time is the increase of series resistance ($R_s$). One of the major sources for the series resistance increase is the degradation of solder bonds between copper ribbon and cell metallization in the cell strings. As a module is exposed in the field, depending on the climatic conditions, the thermomechanical fatigue or IMC (intermetallic compound) formation caused cracks develop in the solder bonds leading to increased series resistance.

Previous studies show that the field exposed modules undergo thermomechanical fatigue which results in changes in the solder-joint geometry thus causing reduction in the number of redundant solder joints and increase in series resistance [1]. A streamlined approach is needed to understand the relationship between the solder bond fatigue, series resistance between various components of a solar cell and the thermomechanical stress. The main objective of this work is to calculate the series resistance for various circuit components and interfaces of the individual cells extracted from field aged modules in three diverse climatic conditions. The cells were cut from the modules, encapsulant was chemically dissolved and the resistance measurements were performed on the IMS (interconnect metallization system). The IMS is comprised of cell metallization and solder bonds of cell strings. After the measurements, peel test experiments were performed to determine the solder bond strength between aged and fresh samples. Finally, climate specific thermal modelling was performed to observe the correlation, if any, between thermal fatigue, series resistance and peel strength.

II. EXPERIMENTAL METHODS

To separate the cells from the field aged module, two methods were developed: chemical and mechanical. In the chemical method, trichloroethylene (TCE) was used using the concept developed by Doi et al [2]. In the mechanical method, a hollow metal bar was used using the concept developed by Nick Bosco at NREL (private communication). For the chemical method, after the cell containing laminate was cut from the module using a dremel tool, TCE was used to dissolve out EVA from the cut laminate piece containing broken glass, EVA, cell and back sheet. In this method, two thick stainless steel metal plates which are little larger than the size of the cell were used as shown in Fig. 1. In one of the plates, about 1 mm diameter holes were made with uniform distance between them. The cell laminate was sandwiched between these two stainless plates and tightly bolted using four corner bolts and nuts. To ensure a good contact between TCE and cell-front EVA, the plate containing holes made in contact with the broken glass superstrate. The whole sandwich containing metal plates and cell laminate was immersed in a 100% TCE solution contained

Fig. 1. (a) Front view of the setup (b) Back view of the setup

Fig. 1. (a) Sample before extraction using TCE method (b) sample after extraction using TCE method
glass beaker. This beaker was then placed in another larger glass beaker containing water. This setup was placed on a hot plate kept inside a fume hood. The solution temperature was raised to 60-80°C and kept at this temperature for 60-90 minutes depending on the need. As shown in Fig. 2, after dissolving out EVA from the cell-front, the entire cell without EVA on the cell-front became available for the planned experiments. Cell extraction using TCE is not expected to have any damaging effect on the solder bonds as it is an organic solvent. To further confirm if TCE causes any damaging effect on the solder bond, the mechanical method was implemented to extract a cell strip along the location and direction of cell busbar. In this method, the back sheet of the desired cell was first cut using a heavy-duty razor blade and a heat gun, and then the back metallization of the cell was removed by polishing with a use of sandpaper and IPA (isopropyl alcohol) as shown in Fig. 3 (a). Once the backside of the cell was polished, a square metal tube was placed on the cell beneath the busbar/ribbon and the cell was cut along the periphery of the metal tube using a heavy-duty razor blade. As shown in Fig. 3 (b), 3M epoxy glue DP 460 was used to glue the metal beam to the backside of the cell and it was allowed to cure overnight. Once the glue was hardened and the beam was stuck to the cell firmly, a heat gun was used and heat was provided from the front side through the glass superstrate of the module over the area of interest (along the metal tube area). By providing heat for about 5 minutes, the EVA on the front side loosened up and the cell strip along metal tube was extracted from the module. It is to be noted that by providing excessive amount of heat, one may melt/affect the solder bond strength which need to be avoided by limiting heating time and temperature. This method is a very cost and time effective method when compared to the TCE method discussed above but a greater caution should be exercised during the heating steps.

One of the most common ways of measuring the resistivity of some thin, flat materials, such as semiconductors or conductive coatings, is to use a four-point collinear probe. The four-point probe technique involves bringing four equally spaced probes in contact with a material of unknown resistance. The instrumentation used for this test includes a DC current source, a highly sensitive voltmeter, and a four-point collinear probe. The four-point probe resistance measurements are done using the SMU 2450 source measurement unit, SP4 - four-point probe head and S-302 test stand as shown in Fig. 4. For the series resistance measurements, all the various combinations possible for causing the resistance were considered. The various combinations used for the resistance measurements are shown in the Fig. 5. The setup was connected to the multimeter and by using the resistance value shown on the multimeter the series resistance was calculated. For a combination between two surfaces, it was made sure that two probes were placed on one surface and the other two probes on the other surface as shown in Fig. 6.

The thermal fatigue is mainly developed due to two factors. The first factor is the daily temperature change that is the day and night temperatures which effects the solder bond gradually by the expansion and contraction of the solder bond. The second factor is the cloud cycles which occur almost every day which cause the sudden expansion and contraction in the solder ribbon.

![Fig. 3. (a) Sample of cell polished on the backside using IPA and sandpaper after extraction using TCE method, (b) Metal beam glued to the cell using 3M epoxy glue](image)

![Fig. 4. Four-point probe test setup](image)

![Fig. 5. Combinations used in four-point probe measurements](image)

![Fig. 6. Placement of probes on the semiconductor](image)
which might induce cracks in it as the time goes on. In this work, the thermal fatigue for 20 years was calculated from 1991 to 2010 to have a better understanding of how much fatigue a module can develop over 20 years in different climates. In order to estimate the fatigue developed, first the total irradiance was calculated using the Liu-Jordan model using Matlab software and also by using PVsyst software by converting the meteorological data into PVsyst format. Once the total plane of array (POA) irradiation is calculated, the cell temperature is calculated by using the following equation [3],

\[
T_{\text{cell}} = T_{\text{amb}} + E \cdot e^{a + b \cdot WS} + E \cdot \left( \Delta T / E_0 \right)
\]  (1)

where a and b were empirically determined for a glass/polymer backsheet module construction deployed in an open-rack configuration to be −3.56 and −0.075, respectively [3]. \(E_0\) is the reference solar irradiance of 1000 W/m², WS stands for wind speed, \(T_{\text{amb}}\) stands for the ambient temperature of the module and \(\Delta T\) represents the temperature difference between the cell and module at this reference irradiance. For an open-rack configuration \(\Delta T\) was determined to be 3°C; however, this offset temperature will be sensitive to racking method and module construction. The thermomechanical fatigue is calculated by using the formula [3],

\[
D = C \cdot (\Delta T)^n \cdot (r(T))^b \cdot e^{\frac{Q}{k_B T_{\text{max}}}}
\]  (2)

where \(\Delta T\) is the mean daily maximum cell temperature change, \(T_{\text{max}}\) is the mean daily maximum cell temperature (calculated using the \(T_{\text{cell}}\) formula above), \(C\) a scaling constant and \(Q\) and \(k_B\) are activation energy and Boltzmann’s constant. The temperature reversal term, \(r(T)\), is the number of times the temperature history increases or decreases across the reversal temperature, \(T\), over the course of a year. The scaling constant \(C\) and the reversal temperature \(T\) were used to fit this model to our simulated data, while the values of the exponents \(n\) and \(b\) and the activation energy \(Q\) are shared with the Coffin-Manson and Norris-Lanzberg equations for Pb-Sn eutectic solder \((C=240, T=56°C, n=1.9, b=0.33, Q=0.12 \text{ eV})\).

### III. Results and Discussions

Dark I-V measurements were performed for the three modules from 3 different climates for all the possible cells. As shown in Fig. 7, the highest drop in the fill factor was observed for the cells from Mexico module (23 years) due to their high series resistance followed by Arizona (18 years) and California module (20 years). The highest drop in the fill factor is observed for the cells from Mexico module due to their high series resistance. The high series resistance is observed due to their high field exposure (23 years) and also due to the climate in which they were exposed (warm and humid). Due to the humid conditions, the moisture ingresses through the backsheet of the modules and creeps into the solder joints causing corrosion which decreases the ribbon contact with the busbar. When this happens, the electrons generated in the cell have to find an alternate but a narrow and long route in order to get transferred from cell to ribbon thus increasing the series resistance. After Mexico module, the worst series resistance is shown by the Arizona field exposed module (514210) which is exposed for 18 years in hot and dry climate. The other exposed module from Arizona (464185) shows series resistance values very close to that of the control module which indicates that the solder bonds in the modules are practically intact and show very less degradation. The California aged module shows higher series resistance when compared to the California control module as expected. California module are expected to have lower series resistance than Arizona modules due to their temperate climate and also due to lesser cloud cycles.

Dark current was passed through the module and the temperature of each cell was measured using infrared (IR) camera. When the temperatures at three different position of a cell are considered, the temperature at the ribbon of the cell is higher when compared to the temperatures at the center and edge of the cell respectively as shown in Fig. 8.
The peel strength of the cell with highest series resistance from each module was compared. From the Fig. 9, it can be observed that the peel strength decreases with series resistance. Cell from Mexico aged module has the highest series resistance thus experiences the lowest peel strength followed by Arizona aged modules 514210 and 464185.

When the results were processed, it was observed that the peel strength decreases with the increase of series resistance. Cells from Mexico aged module has the highest series resistance thus experiences the lowest peel strength followed by Arizona aged modules. Fig. 10 shows the relationship between the module level $R_s$ and the average peel strength of the same module obtained from different cells. The series resistance was calculated by taking the slope of the last few points close to the $V_{OC}$ side of the light I-V curve. From Fig. 10, it can be observed that the peel strength of the module decreases with increase in the series resistance of the module which is like the trend observed when peel strength was compared with cell level series resistance taken from dark I-V curves.

Fig. 11 shows the plot between the peel strength and thermal fatigue accumulated in the module over a period of 20 years from 1991-2010. It can be observed that peel strength and fatigue have no correlation as such. It can be also concluded that lower fatigue does not necessarily imply higher bond strength. In order to fully demonstrate the absence of fatigue vs peel strength, it is recommended to pull one module every year from a plant from a single manufacturer in Arizona as there is no corrosion but only thermal fatigue and generate this plot again.

Peel strength is influenced by both material/design properties and process control as well. Since process control from one manufacturer to another manufacturer varies, no correlation between fatigue and peel strength could be expected.

Fig. 12 shows the relationship between the module level $R_s$ and the thermal fatigue accumulated by the module over a span of 20 years from 1991-2010. From the plot, it can be observed that typically higher thermal fatigue should lead to weakened bond strength due to temperature and cloud cycles which results in expansion and contraction of solder bonds and ribbons. This weakens the interface between ribbon-solder and/or solder-busbar resulting in higher series resistance. However, as shown in Fig. 7 Mexico module (warm and humid climate) has the highest series resistance but not the highest fatigue which implies that not only fatigue, but other factors like IMC formation and corrosion can also aide the increase in series resistance in the presence of humidity/moisture. Therefore,
fatigue alone may not be considered for the series resistance increase/correlation. The four-point probe resistance measurements were performed for modules from 3 different climates. It is to be noted that the control module for both Arizona and Mexico was assumed to be the same. Fig. 13 shows the variation of $R_{\text{Ribbon-Busbar}}$ with Fill Factor for cells from Arizona field aged/control and Mexico field aged modules. As shown in Fig. 13, it can be observed that a decreasing trend is seen in fill factor with increasing resistance. This combination of resistance has the highest values of series resistance when compared to other busbar combinations. In this graph, a higher rate of decrease in fill factor can be seen in Arizona modules than the Mexico module. The placement of the probes for the ribbon-busbar combination is shown in Fig. 14.

It can be observed from Table I that the highest rise in resistance is observed for $R_{\text{Ribbon-Busbar}}$ for both Arizona and Mexico modules and it implies that the interface between the ribbon and busbar is the most affected interface resulting in fill factor drop which in turn leads to power loss. This interface degradation is attributed to the degradation of solder bonds. The resistance of the fingers remained nearly constant irrespective of the change in the fill factor.

### IV. Conclusions

The fill factor and short-circuit current of the test samples are the most affected performance parameters. The fill factor is determined to be affected by the increase of series resistance and the short-circuit current is determined to be affected by the encapsulant browning and series resistance. Temperature of the cell increases with the increase in series resistance. Also, the temperature along the solder in a cell was observed to be higher than the temperatures at the edge and center of the cells. In a module from Mexico where series resistance effect is higher, a 0.05 Ω increase in series resistance causes a 2.7°C increase in temperature near the solder region when compared to 1.07°C and 0.94°C increase in edge and center regions, respectively.

The peel strength of the ribbon-busbar interface decreases with increase in series resistance. The peel strength of the ribbon-busbar interface decreases with increase in series resistance. The major factors that might influence the degradation of the interface are the cloud cycles, IMC formation and also corrosion when the module is fielded in humid conditions. For the module from Mexico, the peel strength decreases by 47% between the lowest series resistance cell and the highest series resistance cell. For Arizona, one module (464185) which has a series resistance of 1.4 Ω had an average peel strength of 3.01N compared to another module (514210) which has a series resistance of 4.49 Ω had an average peel strength of 0.9N. The major factors that might influence the degradation of the IMS are the fatigue due to cloud cycles, IMC formation (between copper ribbon and solder bond and/or solder bond and metallization) due to higher operating temperature and corrosion when the module is fielded in humid conditions. In the four-point probe resistance measurements, it was observed that the ribbon-busbar configuration (solder bonds) was the largest part effecting the series resistance and fill factor. Thermal fatigue developed by the modules over the years due to cloud cycles was investigated to observe if there is
any correlation between thermal fatigue and peel strength. Since peel strength is influenced by a combination of thermal fatigue, IMC formation and corrosion, no specific correlation between only thermal fatigue and peel strength could be established. Mexico module, despite having a lower calculated fatigue, has a high series resistance which is possibly due to the moisture ingress through the backsheet or laminate edges leading to corrosion of metallic components of the cells.

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