Reliability Implications of Solder in Multiwire Modules under Dynamic Mechanical Loading

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Reliability Implications of Solder in Multiwire Modules under Dynamic Mechanical Loading

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***Abstract*—Two generations of multiwire modules were studied under dynamic mechanical loading (DML) with in-situ differential conductance (*dG*) and electroluminescence (EL) imaging. Energy-dispersive x-ray spectroscopy (EDS) was used to identity the solder alloys. The earlier generation module was found to use an In-based solder alloy, and the current generation a Bi-based alloy. The earlier generation module degraded significantly under DML with increasing resistance, while the current generation module did not demonstrate degradation under DML. Atomic force microscopy scratch testing was used to probe the wear resistance of each solder alloy. These results indicate that current multiwire designs may have higher mechanical durability than earlier generations.**

***Keywords* – dynamic mechanical loading (DML), multiwire, low temperature solder, wear, atomic force microscopy (AFM)**

I. Introduction

The majority of commercial photovoltaic (PV) modules today feature cells interconnected by thick busbars soldered with a Sn-Pb solder alloy. Many manufacturers have increased the number of busbars from two to up to five, with multibusbar technologies using 12 or more. Multiwire technologies, such as Meyer Burger's SmartWire Connect Technology (SWCT) [1], [2] or the TWILL-BIPV project from imec [3], employ a distinct approach. In multiwire technologies, the wires are coated with a low-temperature solder such that interconnection occurs during lamination. Due to this reduction in the thermal stresses associated with soldering, multiwire interconnects are favored for temperature sensitive silicon heterojunction (SHJ) cells or for flexible PV technologies using thin, fragile cells [4], [5]. The multiwire design offers increased interconnect redundancy, lower Ag consumption, and reduced shading losses leading to both improved reliability and improved performance [1].

Multiwire modules have been shown to perform well under standard accelerated testing [2], [6], [7]. However, it is likely that distinct testing protocols will be needed for these technologies due to the distinct design, processing, and materials. Previous work indicates that thermal cycling may not be a meaningful test for the low temperature solders used in these interconnections, and that mechanical wear may be a more pertinent failure mechanism [8]. It has been shown that wear resistance is well correlated to the lifetime of electrical contacts [9]. In this work, two multiwire module types are studied: one earlier generation multiwire module and one state-of-the-art, each using distinct solder alloys. The modules are subjected to dynamic mechanical loading (DML) with in situ differential conductance (*dG*) measurements and EL imaging. The mechanical wear resistance of the solder alloys is compared using atomic force microscopy (AFM) scratch testing to demonstrate the alloys' susceptibility to failure under repeated mechanical loading.

II. Experimental Methods

A. Module details

Two generations of multiwire modules were selected for this study. The first is an earlier generation of the multiwire technology and the second is the state-of-the-art. The first module type is a 60-cell mono-crystalline PERC module manufactured by SolarTech Universal before 2018. The second is an REC Alpha module manufactured in 2020 using 120 n-type heterojunction half-cut cells. The solder alloys used in the interconnects were identified through scanning electron microscopy (SEM) and energy-dispersive x-ray spectroscopy (EDS) of cross-sectioned cores. This revealed that the earlier generation used an In-Sn solder alloy, while the state-of-the-art module used a Sn-Bi alloy.

B. Module-level DML and performance monitoring

Dynamic mechanical loading (DML) was achieved through a custom-built system developed previously in our lab [10]. For this DML system, sheet metal is machined to fit and seal the module frame such that two shop vacuums can apply positive and negative pressure. The control instrumentation records the module temperature and cycle pressures. The noise in the pressure sensor measurement is less than 50 Pa, and the setpoint accuracy of the system depends on the ramp rate. Tests were performed to ±1000Pa.

The module under test is also placed under forward bias with an additional sinusoidal voltage such that the *dG* can be measured in situ. The *dG* declines with increasing module temperature due to the effect of temperature on electrical resistance, but the decline is reversible. Irreversible *dG* degradation is thus attributed to module damage. The module temperature increased over test time each session due to the heat generated by the vacuum motors and the constant forward biasing. High-resolution electroluminescence (EL) images and I-V curves were taken intermittently, while lower resolution EL images and video were taken in situ.

C. *Material-level solder characterization via AFM*

For wear characterization, commercially available solder pastes and performs were reflowed under vacuum at 20˚C above their respective eutectic temperatures onto 12x12mm copper substrates. AFM scratch testing was conducted with a BrukerNano Dimension Icon in an Ar glove box. A diamond-coated Si tip from Bruker DDESP was used. Scratches were conducted with forces of 2.8, 4.4, and 6 μN at a speed of 180 nm/s. Scratches were performed in four locations for each solder and the scratches were repeated twice in each location. The depth profiles and scratch lengths were used to calculate the volume of material removed and the contact area of the probe. Mechanical wear can be represented by Archard's wear equation [11]:

$$V = \left(\frac{K}{3H}\right) F \cdot L \qquad (1)$$

where *V* is the volume of material lost, *K* is the wear coefficient, *H* is the Brinell hardness, *F* is the force, and *L* is the length over which the force is applied. For scratch testing, this equation can be rewritten as:

$$A = \left(\frac{K}{3H}\right) \cdot F \qquad (2)$$

where *A* is the cross-sectional area of the scratch indent. Since the hardness *H* is a relatively constant material property within the scope of this study, *K/3H* is used as the relevant parameter for comparing the expected wear between the different solder alloys. Scratch testing can also be used to estimate hardness using:

$$H_s = H_{ref} \left(\frac{L_s}{L_{ref}}\right) \left(\frac{W_{ref}}{W_s}\right)^2 \qquad (3)$$

where *W* is the scratch width and the subscripts *s* and *ref* refer to the test sample and the reference material, respectively [12]. The Sn-Pb solder alloy was used as the reference material in this study.

III. Results

A. *DML*

1) *Early generation module*

The moving average of the *dG* and the module temperature during DML cycling for the earlier multiwire technology is shown in Fig. 1. The gradual decline in dG is seen to correspond to the gradual increase in temperature. The sharper decrease in *dG* of about 10% around 750 cycles is irreversible and attributed to module damage. However, EL imaging after the module temperature returned to ambient showed no damage. The appearance of degradation in the EL images was found to be temperature-dependent, as show in Fig. 2. At higher module temperatures, the degradation appears with more intensity (Fig. 2a) than at lower temperatures (Fig. 2b). A comparison of the I-V curves before and after 6900 cycles of DML demonstrated a 2.8% drop in maximum power due to a decrease in V_{max}, leading to I-V knee rounding.

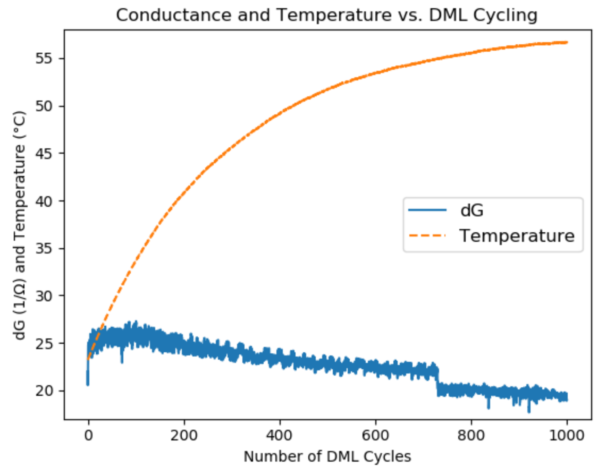

Fig. 1. *dG* (moving average) and module temperature throughout DML for the early generation module.

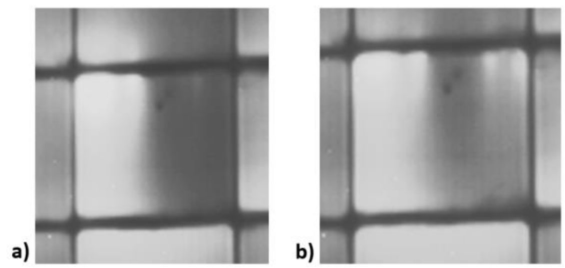

Fig. 2. In-situ EL images of one cell in the early generation module a) right after cycling, T=42˚C and b) after 15 mins. of cooling, T=32˚C.

Four wire/gridline intersections were cross-sectioned, and in all four it was found that the In-Sn solder consumed the Ag gridline. Three of the 4 cross-sections revealed cracks in the solder interface, whether the area cored was degraded or not. Additionally, broken interconnect wires between the cells were found to only explain a small part of the degraded areas.

2) *State-of-the-art module*

The state-of-the-art module had two crossbars mechanically supporting the backside. Initial DML cycles performed with these crossbars intact did not cause any observable degradation. A recoverable decline in *dG* with increasing module temperature was observed in this module, similar to the earlier generation module (Fig. 1). The crossbars were then removed from the module for better comparison to the earlier generation module. The process of removing the crossbars induced damage to the module as shown in the EL images in Fig. 3. An additional 5000 cycles were performed without the crossbars and no *dG* degradation was observed. Removal of the crossbars caused significant cracking, yet few additional cracks were initiated or propagated during subsequent DML. EL imaging detected no other degradation. Flash testing after crossbar removal and after subsequent DML revealed no additional performance losses. These results indicate that DML did not introduce damage to the module, with or without the additional mechanical support of the crossbars.

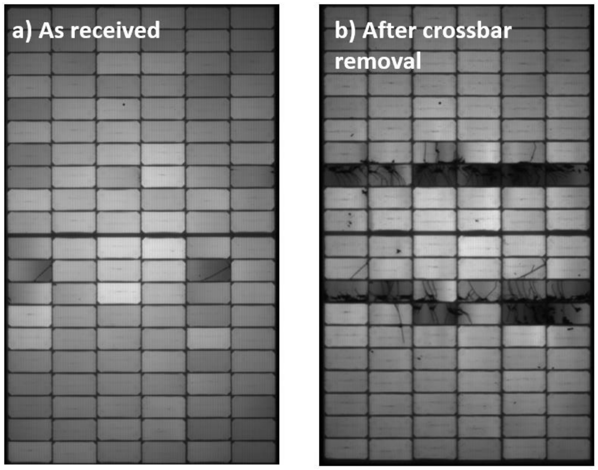

Fig. 3. EL images of the state-of-the-art module a) as received and b) after the crossbars were removed. The process of removing the crossbars damaged the module.

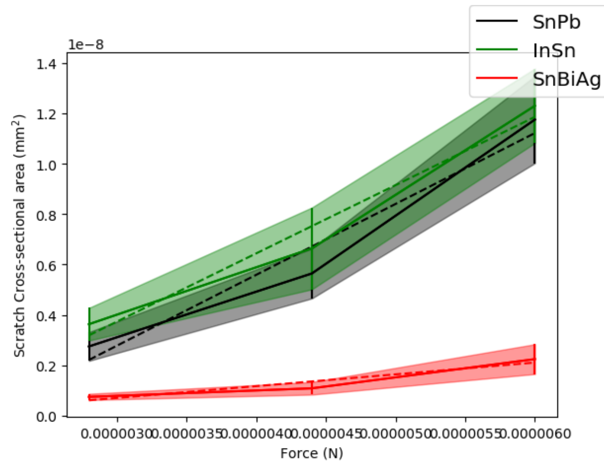

Fig. 4. Scratch area vs. force for conventional SnPb vs. two relevant low temperature solder alloys. The shaded regions indicate standard deviations of the four measurements and the dotted lines indicate lines of best fit.

B. *AFM wear measurements*

The wear resistance of the solder alloys used in multiwire interconnects was assessed using AFM scratch testing. A silver gridline fired onto a cell was also subjected to scratch testing. Using Eq. (3), the gridlines were found to have much higher hardness values than any of the solders based on relative scratch widths. This indicates that the solder materials will wear against the gridlines. The cross-sectional area of the scratch versus scratch force is plotted in Fig 4. The slopes for InSn and SnPb are greater than that of the Sn-Bi alloy. As per Eq. (2), this demonstrates that that InSn and SnPb wear significantly more than the Sn-Bi alloy given the same loading conditions.

IV. Discussion and Conclusion

This study compares two distinct multiwire modules: one earlier generation with an In solder alloy and one current generation with a Bi solder alloy. The earlier generation module showed significant, increasing degradation throughout DML, while the state-of-the-art did not demonstrate degradation. The temperature dependence of the degradation in the earlier module combined with the I-V curve rounding point to issues with the metallization, contacts, or interconnections. As broken wires were not found between the cells for most of the degraded areas, the degradation can be attributed to the wire/gridline interfaces. Cracks in the solder interface were not found to be correlated to the degradation, indicating that additional interfacial damage, such as mechanical wear, is likely a significant factor. AFM scratch testing showed that the solders will sustain wear when in moving contact with the fired silver gridlines. The results also show that the In-based alloy used in the earlier multiwire generation would be expected to wear significantly more than the Bi-based alloy used in the current multiwire products. This qualitatively agrees with the module-level DML results presented here. The earlier module using an In-based solder alloy degraded significantly while the state-of-the-art module did not degrade under DML. These results indicate that current generation multiwire modules using Bi-based solders are likely to be more mechanically durable than the those using In-based solders, which demonstrated interfacial degradation under cyclic loading. Performance data from fielded modules will provide further insight into the durability of multiwire interconnect technologies.

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