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Evaluation of Encapsulant Adhesion to Surface Metallization of Photovoltaic Cells

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***Abstract* — Delamination of encapsulant materials from PV cell surfaces often appears to originate at regions with metallization. Using a fracture mechanics based metrology, the adhesion of EVA encapsulant to screen printed silver metallization was evaluated. At room temperature, the fracture energy, G_c [J/m^2], of the EVA/silver interface (952 J/m^2) was ~70% lower than that of the EVA/AR coating (>2900 J/m^2) and ~60% lower than that of the EVA to the surface of cell (2265 J/m^2). After only 300 hours of damp heat aging, the adhesion energy of the silver interface dropped to and plateaued at ~50-60 J/m^2, while that of the EVA/AR coating and EVA/cell remained mostly unchanged. Elemental surface analysis showed that the EVA separates from the silver in a purely adhesive manner, indicating that bonds at the interface were likely displaced in the presence of humidity and elevated temperature, and may explain the propensity for delamination to occur at metallized surfaces in the field.**

I. Introduction

Delamination of encapsulants from PV cell surfaces introduces pathways for moisture ingress, which eventually leads to reduced cell performance. In the field, delamination at the cell interfaces often originates at metallized regions, such gridlines and bus bars. While studies have investigated the adhesion of encapsulation to cell surfaces, none have resolved adhesion properties at each constituent surface material, in particular the screen printed silver gridlines. A quantitative characterization of gridline adhesion and identification of relevant failure mechanisms is critical for developing predictive degradation models and engineering new materials to extend module lifetimes.

A recently developed metrology for measuring the adhesion energy of module interfaces [1-2] was used to evaluate adhesion of encapsulation to each material on the surface of a PV cell. First, baseline measurements of the adhesion energy of ethylene vinyl acetate (EVA) to screen printed silver, the silicon nitride anti-reflective coating, and a commercial silicon PV cell were conducted. Adhesion energy was then measured after 100, 300 and 1000 hours of damp heat aging. While aging had minimal impact on adhesion of the EVA/AR coating and EVA/cell interfaces, adhesion of the EVA/silver interface dropped by over 94% from the baseline value. The failure mode was purely adhesive, with the likely mechanism of degradation being bond displacement at the silver interface in the presence of water at elevated temperature.

II. Methods and Materials

A. Sample Preparation

One-cell PV modules were fabricated by laminating EVA between a 150 mm x 150 mm silicon cell and a 3 mm thick glass substrate for each of three cell configurations: (a) coated entirely with a ~30 micron thick layer of screen printed silver (Fig. 1a), (b) covered with an AR coating and screen printed silver gridlines (sell surface), and (c) covered only with and AR coating.

Width-tapered titanium (Ti, 6%Al, 4%V) beams 1.86 mm thick were then bonded to cell on the rear surface of the modules using a metal bonding agent (DP-420, 3M). Modules were aged at 85°C, 85%RH in an environmental chamber (AES, Santa Clara, CA) for intervals of 100, 300 and 1000 hours. Upon removal from the chamber the modules were conditioned at room temperature for an hour. During this time, a diamond scribe was used to dice the cell along the perimeter of the titanium beam, forming a composite EVA/cell/titanium adhesion specimen directly on the module.

B. Adhesion Metrology

Adhesion was measured by loading the wedge shaped beam directly at its apex (Fig. 1b) such that a crack initiates along the EVA/cell interface. The adhesion energy of the interface is a direct measurement of the critical energy release rate, G_c [J/m^2], required to propagate the crack, and for a width-tapered beam is given by [1-2]:

$$G_c = \frac{P_c}{2\tan(\theta/2)}\frac{\Delta_f}{a_f} \qquad (1)$$

where P_c is the critical applied load, Δ_f is the displacement at the beam tip corresponding to a crack length, a_f, and θ is the apex angle.

C. Surface Chemistry Analysis

Chemical composition of complementary fracture surfaces from several adhesion specimens was conducted using X-ray photoelectron spectroscopy (XPS, PHI VersaProbe) with a 200 µm spot size. Depth profiles were collected via argon ion sputtering.

III. Results and Discussion

Baseline measurements of the adhesion energy of EVA to the screen printed silver, cell surface and AR coating were, 952 ± 26, 2265 ± 67 and >2896 J/m^2, respectively. Note that the intermediate adhesion energy of the cell surface is lower than a rule of mixtures approximation (~2800 J/m^2) calculated using proportional surface coverage of the gridlines and AR coating.

Adhesion energy values following damp heat aging are presented in Fig. 2. After 100 hours, the adhesion energy of the EVA/silver interface dropped to 651 ± 28 J/m^2, while the AR coating (>2900 J/m^2) and cell surface (2441 ± 127 J/m^2) exhibited no measureable adhesive degradation. By 300 hours the adhesion energy of the EVA/silver interface again dropped to an apparent threshold (~50-60 J/m^2), at which point there appeared to be no further degradation with continued aging. (Currently the AR coating and cell surface specimens are still undergoing 300 and 1000 hour aging; results for those specimens will be presented in the final paper).

XPS analysis of the unaged silver screen print (Fig. 3a) indicated the surface consisted of silver, lead (a precursor in screen print synthesis), oxygen (from silver and lead oxides), and trace amounts of chromium and carbon (the latter attributed to atmospheric contamination). The composition was nearly all silver after ~4 nm of depth profiling. The presence of an oxide layer on the surface screen print is in fact desirable, as the adhesion energy of EVA to pure, evaporated, silver was previously measured to only be 20.5 ± 5.4 J/m^2.

Analysis of the fracture surface of silver screen print following 100 hrs of damp heat aging showed no change relative the unaged screen print. The complementary EVA fracture surface (Fig. 3b) consisted entirely of carbon, oxygen and silicon (from the silane adhesion promoter in the EVA formulation), with no traces of silver or lead from the screen print. This indicates that the mode of failure at the EVA/screen print interface was completely adhesive. The likely mechanism of degradation is bond displacement between the silver and EVA interface in the presence of moisture at elevated temperature (this is being further investigated and will be discussed in the final paper).

Evaluation of fracture surfaces from the 100 hour EVA/cell adhesion specimen yielded a similar result; silver screen print material was detected on the cell surface along a gridline, but was not detected on the complementary EVA surface, indicating adhesive failure. EVA, however, was detected on the AR coating regions of the cell surface, but was removed after 10 to 20 nm of depth profiling, indicating cohesive failure (in the EVA) near the interface.

During baseline adhesion testing of the EVA/cell specimens, cavities developed along the interface (with no preference for AR coating or gridline) in a cohesive ahead of the crack front (Fig. 4a). After aging in damp heat, however, cavities and subsequent delamination preferentially initiated at the gridlines. Similar behavior has been observed in previous work, where fully encapsulated modules with backsheets were lab aged at 85°C, 13.5%RH for 1000 hours (Fig. 4b) as well as field aged in various environments (Golden, Miami, Phoenix), indicating that adhesive degradation at the EVA/gridline interface similarly occurs in environments less severe than damp heat.

IV. Conclusions

We have presented for the first time a quantitative characterization of EVA encapsulation to the screen printed silver metallization of PV cells. The as-fabricated adhesion energy of the EVA/gridline interface was just 30% of the EVA/AR coating interface, and degraded with exposure to damp heat, eventually reaching a threshold between 50-60 J/m^2 after 300 hours.

The EVA/AR coating and EVA/cell interfaces did not experience adhesive degradation after 300 hours of damp heat. However, the gridline regions of the cell surface preferentially delaminated during adhesion testing, indicating adhesive degradation of the EVA/silver interface. Similar behavior was observed in specimens aged in less severe lab (85°C, 13.5%RH) and field environments.

XPS analysis of specimen fracture surfaces indicated that the failure mode of the EVA/gridline interface was adhesive, whereas that of the EVA/AR coating interface was cohesive. Although the mechanism of failure at the EVA/gridline interface is currently being investigated, it is likely that bond displacement occurs between the silver and EVA interface in the presence of moisture at elevated temperature. Future work will incorporate finding from this study into the development of a predictive model of adhesive degradation in PV modules.

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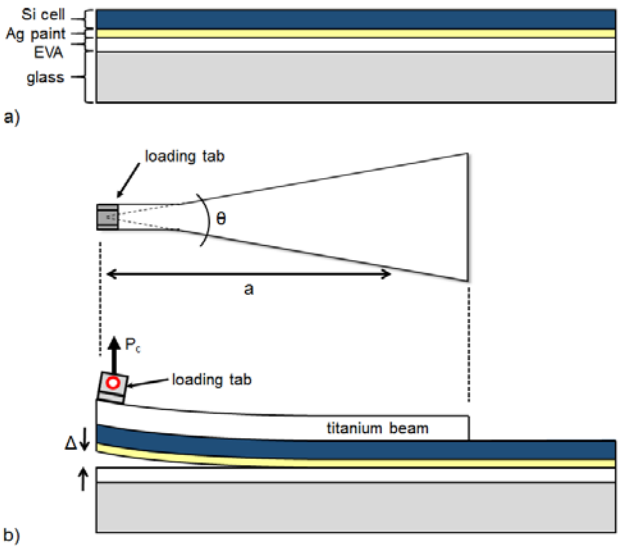

Fig. 1. (a) representative cross-section of EVA/screen print module configuration. (b) schematic of width-tapered beam adhesion specimen.

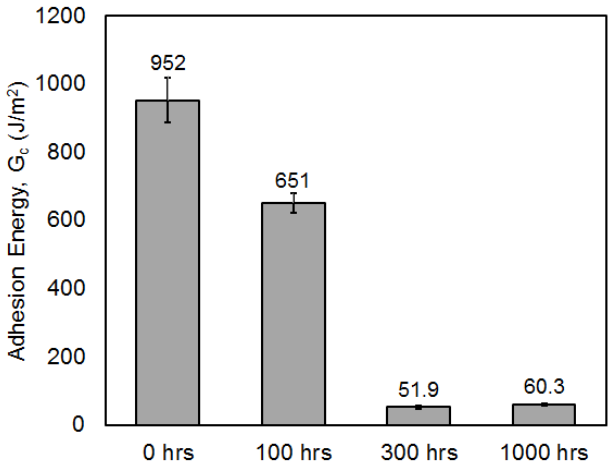

Fig. 2. Adhesion energy of EVA/screen print interface after damp heat aging.

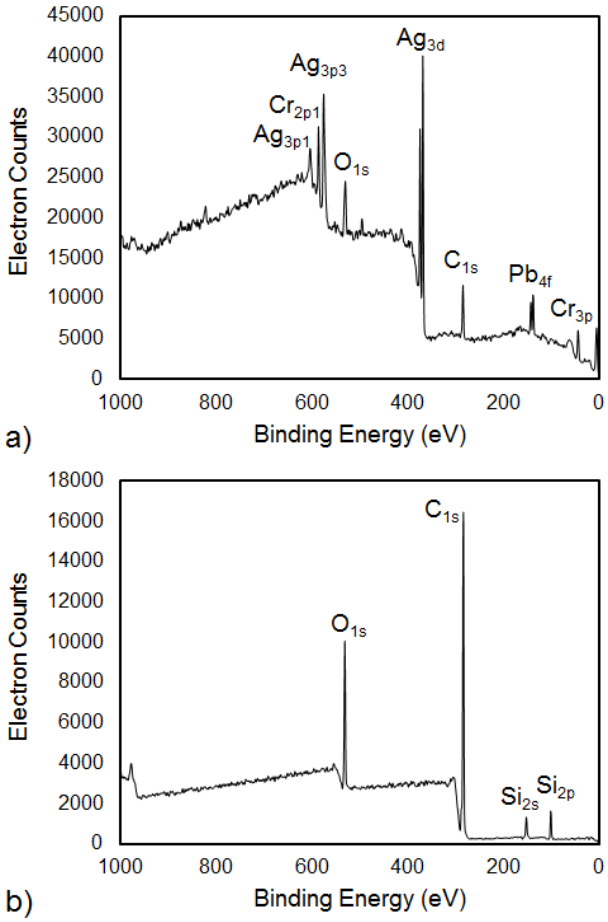

Fig. 3. (a) XPS survey of silver screen print showing the surface is covered with a thin layer of oxide. (b) EVA side of EVA/screen print fracture surface after 300 hours. The absence of screen print components indicates an adhesive failure mode at the interface.

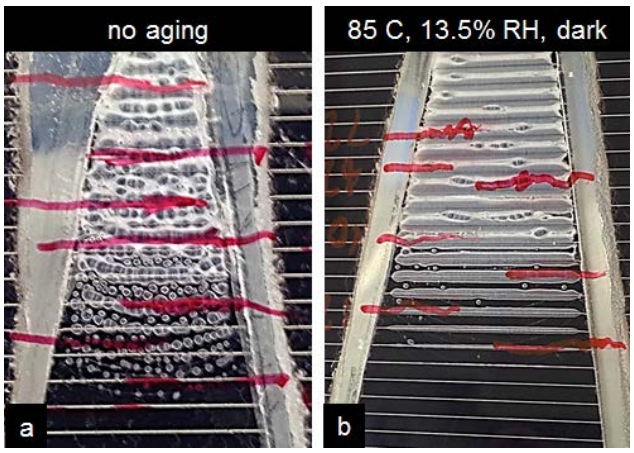

Fig. 4. Images of EVA/cell interface capture during adhesion tests before (a) and after (b) aging at elevated temperature. Following aging, cavities in the cohesive zone of the fracture path preferentially form at gridlines.