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The Effect of Laminate Construction and Temperature Cycling on the Fracture Strength and Performance of Encapsulated Solar Cells

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Abstract **— A critical aspect of silicon solar module reliability is the fracture characteristics of the solar cells under mechanical loads. Here, we use 3-point bend testing of coupons to investigate the effects of tabbing, encapsulant and thermal history on the fracture strength of silicon solar cells. We find that the fracture strength depends significantly on the encapsulant modulus and thickness. Doubling the encapsulant thickness can increase the load at fracture by 80%. In addition, short exposure to low temperatures (< -20C) can decrease the room temperature fracture strength by 80% or more. The mechanism of this effect is described as contraction of the encapsulant thickness adjacent to the ribbon which bends the cell sharply over the ribbon. This low temperature effect on crack susceptibility is not currently captured in standard durability testing sequences. Finally, the amount of crack damage depends on the strain at fracture and the power loss can be as high as 30%. Degradation behavior in extended temperature cycling of fractured cells also depends on the initial fracture pattern.**

Index Terms **— cracks, mechanical load testing, photovoltaic modules, solar panels, reliability, silicon.**

I. INTRODUCTION

Cell cracking is a significant degradation mode for silicon solar modules [1]. Standard module construction consists of a glass superstrate with solar cells encapsulated on the back side of the glass. When the glass deflects downward due to a load such as wind, snow or stepping, the cells can reach a state of high tensile stress which can result in cracks in the cells. The crack damage can vary from a line crack with minimal immediate power loss to a more severe shattering of much of the cell which results in significant power loss.

Recent studies have shown 4-point or 3-point bending of coupons to be a useful method for studying the crack behavior of encapsulated silicon solar cells [2]. Cell cracking behavior is affected by the intrinsic strength of the cell as well as many aspects of the packaging. How much stress the cell is subjected to depends, for example, on the tabbing process and ribbon wire, encapsulant and lamination process, glass, frame, mounting, etc. Here, we investigate the tabbing and encapsulant effects as well as the effect of thermal cycling. Sander and Dietrich [2] have shown that temperature cycling can cut the room temperature fracture strength of silicon cells in half and that encapsulant modulus is a significant factor. Others [2]-[5] have also shown the significance of encapsulant modulus. The results we present here are consistent with those findings. In addition, we characterize the performance loss due to the initial crack event as well as subsequent extended thermal cycling. These results have implications for the design of robust solar panels as well as the test methods and test sequences used in reliability and certification testing.

II. EXPERIMENTAL METHODS

Single solar cells were laminated in a conventional package using 3.2 mm thick 8” x 8” float glass superstrates. Only one type of solar cell was used: a monocrystalline PERC cell with 3 segmented busbars from a leading manufacturer. For cells that were tabbed, 1.5mm x 0.2mm (Cu dimensions) ribbon was used unless otherwise noted, and the tabbing was done on an automated NPC hot-air tabber-stringer. All ribbon types used have a total solder coating thickness 0.03mm (e.g. a 0.2mm ribbon has an actual thickness of 0.23mm). For cells that were laminated with unsoldered ribbon, ribbon was taped to the encapsulant off to the side of the cell. Any sample with ribbons that shifted during lamination were discarded. For samples subjected to temperature cycling, the profile is a rapid cycle (16 cycles/day) and samples see a dwell time at temperature of ~10 min). 3-point bend testing was performed at room temperature, a center deflection rate of 2.5 mm/min and with busbars centered and aligned parallel to the rails of the bend fixture (188 mm lower rail span) so that the applied stress field is perpendicular to the busbars. We have found that this is the weaker orientation, consistent with the findings of previous studies [6]. The stress field and fracture pattern that results from this orientation is also more consistent with the predominant stress field and fracture patterns observed in pressure loading of conventional full size modules [7].

III. RESULTS AND DISCUSSION

We encapsulated solar cells with three different types of encapsulants with different Young’s moduli. The modulus ranges from 10MPa to 35MPa at room temperature (taken from dynamic mechanical analysis curves provided by the manufacturer). The 15MPa material is EVA laminated at 145C and the other materials are polyolefin (PO) encapsulants laminated at 165C. Fig. 1 shows that the fracture strength decreases significantly with increasing modulus and it also decreases significantly with tabbing. The difference between a

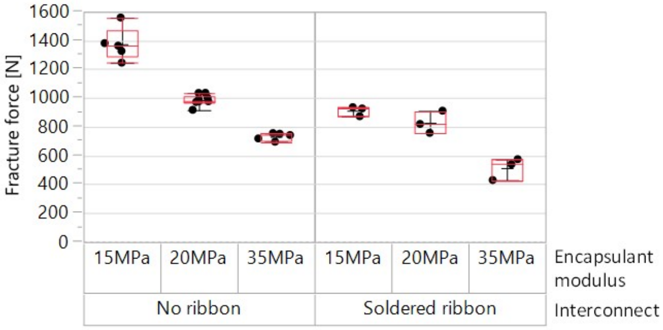

Fig. 1. Fracture force for solar cells encapsulated with three materials of different moduli, tabbed and untabbed.

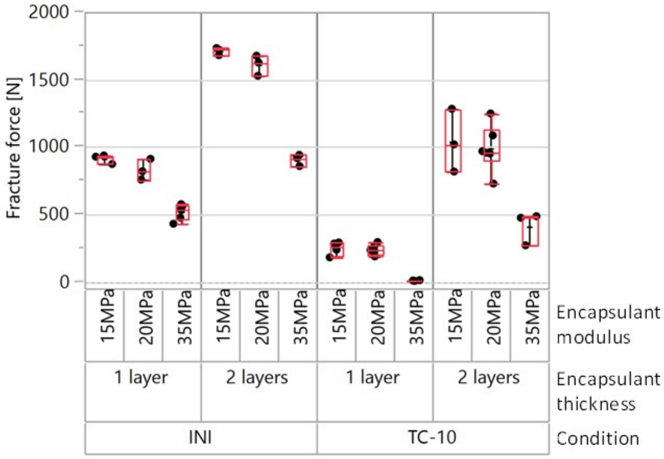

Fig. 2. Fracture force for tabbed solar cells before and after 10 temperature cycles (-40C to 85C). Samples with one additional layer of encapsulant between the cell and glass have a significantly higher fracture strength.

10MPa and 35MPa encapsulant is nearly a two-fold difference in fracture strength. The fracture strength of a tabbed cell is significantly lower than that of an untabbed cell. The drop in strength is slightly worse for the two PO's.

Fig. 2 shows that increasing the thickness of the front encapsulant also has a significant effect on the fracture strength. All three encapsulant types show an increase of approximately 80%. Fig. 2 also shows that temperature cycling (-40C to 85C) of only ten cycles has a significant damaging impact on the fracture strength, reducing it by 80% or more for the samples with the standard configuration of one layer of encapsulant in the front and back of the cell. For the 35MPa encapsulant, the cells were already visibly fractured in photoluminescence images (PL) after TC-10. For samples with a double layer of encapsulant between the cell and glass, the strength also drops significantly after TC-10 but the drop is less than that for single layer coupons, and the final strength is comparable to the initial strength of the single layer coupons. This shows that thicker front encapsulant may be an effective way to mitigate the effect of low temperature exposure. However, note that thicker or softer encapsulant may affect interconnect reliability [8]-[9]

The effects of encapsulant thickness and modulus on initial fracture strength can be qualitatively explained by the effect on coupling of the cell to the glass. As the glass is deflected downward, the lower surface of the glass lengthens, resulting in a shear force on the encapsulant that is transferred to the cells. Increasing the thickness or lowering the modulus of the encapsulant between the cell and the glass will further decouple the strain of the glass from the cell. It is also worth noting that the data for the 35 MPa PO is not in agreement with FEA modeling in ref [3] which showed that stiff encapsulants would benefit from a thinning of the encapsulant because the cell will be closer to the neutral axis of the laminate. In this work, we see that all encapsulants show a similar benefit from thicker front encapsulant.

The mechanism of the temperature cycling effect on fracture strength is not so easily explained. The cells are tabbed and laminated at high temperatures and residual stresses develop and increase as the cells are cooled from soldering temperatures over 200C and the lamination temperatures of 145C or 165C down to room temperature and further down to -40C. Silicon has the lowest coefficient of thermal expansion (CTE) of any of the materials in the tabbing or packaging, so contraction of the glass and ribbon will apply significant compressive stress to the cell at low temperature. The stresses in the silicon will be mostly compressive, however, non-uniformities, namely due to the geometry of the ribbon, will cause regions of high tensile stress. In addition, thermal cycling may lead to work hardening of the Cu, exacerbating these affects.

However, recently Sander et. al. [10]-[11] and Dietrich et. al. [12] have described an additional source of stress due to the contraction of the encapsulant and we believe this model explains the effects of low temperature exposure seen in this work. With FEA, they show that as the temperature decreases after lamination, the encapsulant, which has a significantly higher CTE than any of the other materials, contracts and becomes thinner and the cell is pulled closer to the glass. During lamination, the ribbon displaces much of the encapsulant between it and the glass so that the encapsulant is much thinner over the ribbon than adjacent to the ribbon. Consequently, the total encapsulant shrinkage and thickness decrease adjacent to the ribbon is greater than over the ribbon. This results in the cell being bent over the ribbon as the temperature decreases from the lamination temperature. Due to the abrupt change in thickness, the bend is sharp and the tensile stress on the back of the cell may be high enough to cause microcracks or even larger cracks at very low temperatures. Because the region of tensile stress is very localized, any cracks that form in this state will also be localized. However, these cracks represent permanent damage and when the laminate is subsequently bent—at low temperature or high temperature—these cracks may grow at relatively low stresses.

We performed several additional experiments to explore this theory. Fig. 3 shows that the room temperature fracture strength begins to decrease significantly for coupons previously exposed to a single half cycle at temperatures below -20C (e.g. 25C to -20C to 25C). While we have not performed experiments running a large number of cycles at moderate temperatures, the fact that damage occurs with a single low temperature exposure and that the damage is identical to the damage after TC-10, suggests that the mechanism is related to the elastic-brittle nature of the silicon as opposed to work hardening of Cu and an increase in residual stress. We also point out that the coupons are being exposed to low temperature without any mechanical load. It seems likely that the addition of a load could result in even less extreme temperatures causing degradation in the fracture strength [5].

Fig. 4 shows several experiments with different ribbon configurations. Several of the configurations, with and without temperature cycling, are with ribbons simply placed on the cell without soldering. It is notable that these samples show similar behavior as soldered ribbons. This indicates that the Cu connection to the cell and any transfer of thermo-mechanical shear stress is not important, which is again more consistent with the model attributing low temperature exposure damage to the encapsulant shrinkage. However, it is likely that during lamination, encapsulant penetrates some distance under the ribbon and the thinness of this encapsulant could conceivably make a bond that behaves similar to a solder bond at low temperature. Never-the-less, it is a striking result and we believe it is most consistent with the encapsulant shrinkage theory.

Fig. 4 also shows that there is no effect from TC-10 exposure for cells that are tabbed and then temperature cycled before lamination (“Soldered, TC-10 bare”). This again is some indication that the contraction of the Cu is not the cause of the low temperature exposure damage. However, the stress the Cu imparts in the unencapsulated condition is likely different than in the encapsulated condition, therefore we cannot make definitive conclusions based on this data. The last two groups in Fig. 4 are for narrower and thinner ribbon, respectively. Ribbon width does not appear to be a factor but ribbon thickness is a significant factor. A ribbon thickness reduction of only 50um completely eliminates the low temperature exposure effect, at least at -40C exposure. Similarly, it stands to reason that ribbon thicker than 0.2mm will show damage at temperatures even more moderate than -20C.

It is our opinion that all the observations shown here are more consistent with a model described by the contraction of encapsulant thickness causing microcracking in the silicon as opposed to a model described by the contraction of the glass and Cu causing microcracking or increased residual stress.

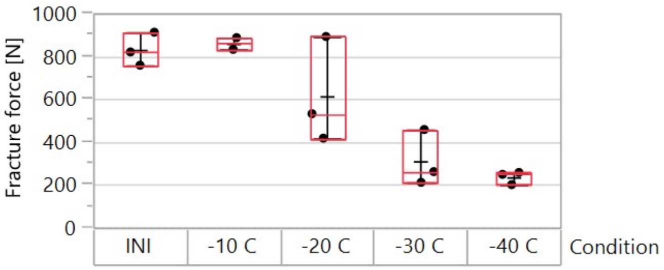

Fig. 3. Load at fracture for low T exposure of a single half cycle (e.g. 25C to -10C to 25C) for tabbed cells encapsulated with EVA. At exposure to -20C, significant damage begins to occur.

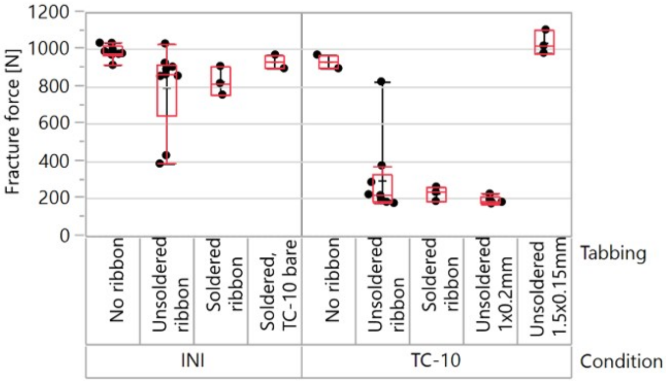

Fig. 4. Fracture force for various laminate constructions before (INI) and after temperature cycling (TC-10).

For coupons tabbed and laminated with a single layer of EVA, we measured the current-voltage (IV) output before and after fracture. Fig. 5 shows electroluminescence (EL) images and power loss as a function of the load at fracture. The crack damage and power loss increases when the fracture occurs at a higher load. As the load increases, the strain energy in the cell increases and at the fracture event much of this energy is released in the form of fracture surfaces. Ideally, cells will be strong enough to avoid cracking at any realistic load. However, if this is not possible, one could argue that weaker cells that fracture at a lighter load will perform better. Alternatively, module designs that reduce the strain cells are exposed to, e.g. thicker front encapsulant, will reduce fracture rates without increasing fracture damage.

The fracture pattern observed in 3PB is similar to the pattern observed in some locations in a full size module under pressure load. However, it should be noted that in many locations on the module, the stress field is quite different and the fracture strength and crack pattern is also different.

The change in the shape of the IV curve is consistent with losses due primarily to recombination at the new crack surfaces. Even for the badly shattered samples fracturing above 700N, the shunt resistance, while degraded, is greater than 3kOhm-cm^2 and the series resistance shows little change. It is also worth noting that the short circuit current (Isc) decreases by only 3% for this group, which is unlikely to result in reverse bias and hotspot conditions in the field. However, stronger cells that fracture at higher strains or cells with high lifetimes and high Voc will show more significant degradation and could result in hotspots. In addition, we also note that the 3PB test applies a more limited stress field than four point bending or loading conditions typical in full size modules. This could reduce the extent of the fracture pattern and the resulting damage.

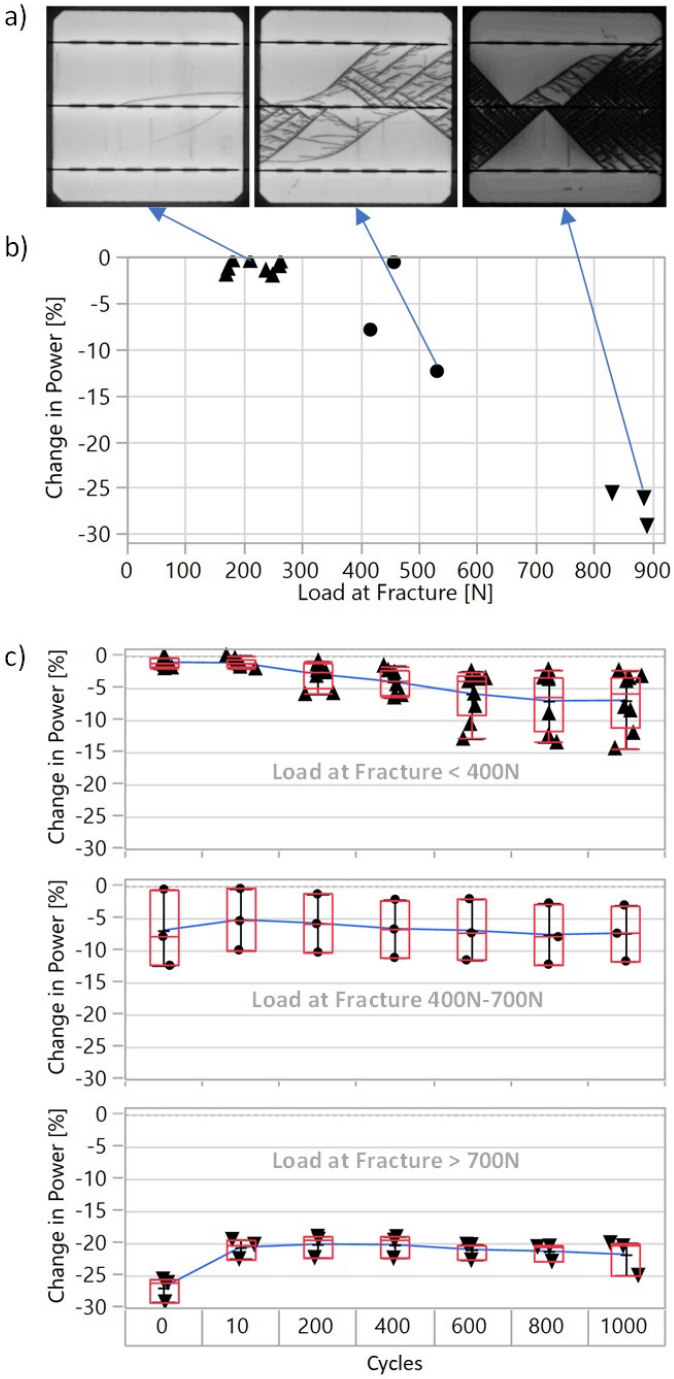

Fig. 5. a) EL images (taken at 0 load, constant current and exposure time), b) Change in Power vs load at fracture for single cells laminated with one sheet of EVA, and c) Change in power for the same coupons subjected to temperature cycling broken out by fracture strength range.

Fig. 5 c) shows the results of extended temperature cycling on the same coupons plotted in Fig. 5 b). The data is broken in to three bins corresponding to fracture at light, medium and heavy loads. There is a difference in TC behavior for the lightly and heavily fractured samples. The samples with light fractures primarily have only a few line cracks and none of the dendritic crack pattern seen in the cells fracturing at heavy loads. These cells with line cracks show typical TC behavior of slow degradation due to finger breaks at the crack lines which increases the series resistance.

The heavily shattered cells show a very different response. Initially they recover nearly a quarter of their power loss, primarily in the FF. One possible explanation of this recovery is oxidation which may reduce recombination velocity at the crack surfaces. Coupons subjected to 100 hours of damp heat (85C/85% relative humidity) show a similar initial response.

Additional temperature cycling has a more modest effect on these heavily fractured samples. Close inspection of the EL images shows few broken fingers even after 1000 cycles and this may be due to the fact a greater number of cracks may mean less movement over each individual crack which will reduce finger fatigue at each crack.

IV. CONCLUSION

We have shown that a single exposure to low temperatures can have a devastating effect on the fracture strength of silicon solar cells. Multiple experiments are consistent with the model of contracting encapsulant bending the cell over the ribbon. The resulting high tensile stress on the back of the cell causes microcracks that permanently degrade the fracture strength of the cell. Because silicon is an elastic-brittle material, only one short exposure to low temperatures is necessary to cause the effect.

While more studies are needed to determine if these effects are significant to degradation in the field, these findings suggest standardized testing methods may not be capturing an important reliability risk and it may be necessary to incorporate a test sequence where modules are pre-conditioned with low temperature exposure prior to mechanical loading tests. This work shows the potential significance of such a change. It is worth discussing what temperature would represent an appropriate acceleration factor. The standard TC test of -40C to 85C for hundreds of cycles is appropriate for accelerating metal fatigue of front contact solar cells and adhesion failures even though -40C rarely occurs in the field. The same test may not be appropriate for accelerating the fracture of a brittle material such as silicon. A more appropriate temperature for preconditioning may be the minimum temperature modules would expect to see in their lifetime, and the time needed to perform the preconditioning could be < 1 hour.

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