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Effects of Accelerated Exposure Testing (AET) Conditions on Performance Degradation of Solar Cells and Encapsulants

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ABSTRACT

This paper briefly summarizes the results from several accelerated exposure tests (AET) studies. A range of light intensities (~1.2 to 9 UV suns) and heating at different black panel temperatures (BPT, 65^o to 145^{o}C) were used to evaluate optical and electrical materials performance and photothermal stability of laminated photovoltaic (PV) cells of various configurations. The results show that optical changes (transmittance (%T), and yellowness index (YI)) of encapsulants were strongly affected by the AET conditions. In contrast, irregular changes in I-V parameters (J_{sc}, J_{max}, V_{oc}, V_{max}, fill factor (FF), and efficiency) of solar cells were observed, which could not be fully attributed to observed optical changes in transmittance (%T) or yellow-browning of superstrate/pottant materials. Causes responsible for the photothermal instability of the encapsulated Si solar cells appear to be multiple and complex.

1. Introduction

The long-term objective of achieving a 30-year service life for PV systems compels application of reliable and durable materials-systems for current PV technologies in order to realize a clean, economically competitive, reliable, and efficient power delivery alternative. Attaining increased module performance, reliability, and durability in an effective, timely manner predicates use of accelerated test methods to help identify and quantify the complex degradation mechanisms. In this study, we employed various AET conditions to evaluate performance stability of solar cells and encapsulation materials.

2. Experimental

Several sample sets were studied for changes before, during, and after various AET exposures. Sample configurations incorporating most features found in typical c-Si PV modules are given in Table 1 and reference [1]. Details of analytical methods are described in [1]. The values in Table 1 are calculated changing rates of electrical and optical parameters per exposure hour. This allows direct comparison with an assumption that the changes are linear, upon completion of AETs.

3. Results and Discussion

Optical Changes of Superstrate/Encapsulant Layer

As seen in Table 1, applied AET conditions strongly affect encapsulant discoloration rates and %T changes in the samples. Following AET, all encapsulant samples typically show a net %T loss in the UV-visible (290-800 nm) range. Ethylene-vinyl acetate (EVA) discoloration rates resulting from AET with ultraviolet (UV) light and heat are generally faster and greater than the rates of samples heated in a dark oven. Discoloration rates of EVA typically depend on the formulation. For example, the regular-cure A9918 discolors to a greater extent than fast-cure 15295 EVA; the latter to a greater extent than NREL-V11 EVA [1]. No discoloration of EVA pottants was observed on the samples that are laminated with stable polymer films such as Tefzel or Tedlar that are permeable to oxygen and permit photobleaching [1]. Instead, the polymer/EVA laminates produced small increases in %T at wavelengths in the UV-region, due to photodepletion of UV absorbers if used in the EVA formulation. When an opaque white substrate layer, such as Tedlar/polyester/Tedlar (TPT), was used, then following AET, a low level of TPT discoloration contributed to the total %T and YI changes observed. Furthermore, light reflection from the white TPT layer enhanced the measured solar cell efficiency.

Electrical Changes of Encapsulated Solar Cells

Although %T loss is generally seen for the glass superstrate laminated EVA upon AET treatments, few changes in the solar-cell I-V parameters were observed which were logically consistent with the %T losses alone. Based on the measurement uncertainty of ~2%, which were established using a working reference solar cell, the measured I-V parameters and calculated changing rates resulting from AET treatments appear to be irregular as indicated in Table 1. The values of V_{oc} for all cell samples did not show significant changes and thus are not shown here. Only those samples with substantial EVA browning would clearly show a corresponding efficiency loss. For example, samples (ECIS-09, 18) subjected to ~9 UV suns at 145^{o}C exhibited a %T loss rate of 4.07-4.66 x 10^{-2}/h with a corresponding, but not proportional, 1.80-2.90 x 10^{-2}/h loss rate in efficiency. Similar results are obtained for the c-Si solar cell samples exposed to ~6.5 UV suns at 65^{o}C and heated in a 105^{o}C oven. In contrast, several of the cell samples exposed to 7.5 UV suns at 85^{o}C (ECIS-06, 22), 1.2 UV suns at 65^o-85^{o}C (ECIS-04, 17), and heating at 85^{o}C (ECIS-07, 19) show an increase in J_{sc} and efficiency, while their %T shows net losses. Interestingly, most of these cells exhibit a net loss rate in FF. Other samples show a mix of either an increase or decrease in efficiency and FF with a net %T loss. A particular case was observed for Tedlar/silicone/Tedlar-laminated c-Si solar cells (e.g., D1-2 and D2-1) exposed to a 1.2 UV suns at 60°-65°C. The cells showed a net %T gain rate of 4.22 and 5.66 x 10^{-3}/h due to photobleaching of the silicone thin layers, but a net loss rate of 1.34 and 2.39 x 10^{-2}/h in efficiency, respectively. This was tentatively attributed to a yet-unidentified chemical attack on cell contacts by photodecomposition compounds from silicone upon AET exposure [1].

To separate electrical (I-V) change of the solar cells from optical change of the encapsulant, NREL-developed V11 EVA was used for its greatly improved photothermal stability against discoloration [1]. Even so, the cells (BP-C4 and HT-C1) still show a net loss in J_{sc}, FF, and efficiency while the %T loss rates are low. More details are described in references [1] and [2].

4. Conclusions

Optical properties for layered superstrate/encapsulant were shown to typically decrease upon AET treatments, except for those with a polymer superstrate or substrate that allows photobleaching of the encapsulant. Changes in solar cell performance are found to be irregular. The irregularity appears to be independent of the AET conditions and optical changes. Transmission losses alone are insufficient to explain all the observed electrical performance losses. Causes responsible for photothermal instability of the encapsulated Si solar cells in this study appear to be multiple and complex. To provide a cohesive explanation of the irregular changes in solar cell I-V performance, more detailed studies and analysis of electrical degradation mechanisms are required.

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[1] F. J. Pern and S. H. Glick, "Photothermal Stability of Encapsulated Si Solar Cells and Encapsulation Materials upon Accelerated Exposure", Solar Energy Materials and Solar Cells, 61 (2000) 153-188.

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Table 1. Changing Rates of Electrical and Optical Parameters for Some Encapsulated c-Si Cells upon AET Treatments

	Measurement Uncertainty (±%):			2.35	1.11	1.75	0.63	4.79 [1]
	Standard Deviation/Average (%):			1.87	0.66	1.39	0.35	3.23 [1]
Sample ID	**Super-strate**	**Pottant Type**	**Substrate**	**Δ J_{sc} (mA/cm^2-h)**	**Δ FF (%/h)**	**Δ Eff. (%/h)**	**Δ %T (%T/h)**	**Δ YI (YI/h)**
AET Condition: 0.0 UV Sun (Oven) at BPT = 85°C (Glass = 3.175-mm (1/8-in.) thick borosilicate plate)								
ECIS-03	Glass	15295P	Glass	-1.82E-3	-1.29E-3	-3.40E-3	-4.55E-4	6.47E-4
ECIS-07	Glass	15295P	Glass	9.62E-3	-4.61E-3	4.36E-3	-1.83E-3	4.59E-4
ECIS-19	Glass	A9918P	Glass	7.14E-3	2.16E-4	7.44E-3	-8.22E-4	2.08E-4
AET Condition: 0.0 UV Sun (Oven) at BPT = 105°C (TPT = opaque white Tedlar/Polyester/Tedlar trilaminate)								
HT2-A1	Glass	15295	TPT	-2.57E-3	-2.76E-3	-4.21E-3	-1.23E-3	2.82E-3
HT2-B1	Glass	15295	Glass	-1.14E-3	-4.36E-3	-5.30E-3	-1.59E-3	4.50E-4
HT2-C1	Glass	NREL-V11	TPT	-1.48E-3	-6.35E-3	-7.65E-3	-2.09E-3	2.67E-3
AET Condition: ~1.2 UV Suns at BPT = 60°-65°C								
ECIS-04	Glass	15295P	Glass	9.87E-3	-1.06E-3	8.58E-3	-1.26E-3	-1.41E-5
ECIS-16	Glass	A9918P	Glass	5.50E-3	-1.72E-2	-1.37E-2	-7.51E-4	3.87E-4
A2-2	Tedlar	EVA	Tedlar	7.74E-3	-1.09E-3	6.06E-3	9.26E-4	-
D1-2	Tefzel	Silicone	Tefzel	-1.91E-2	8.33E-3	-1.34E-2	5.56E-3	-
D2-1	Tefzel	Silicone	Tefzel	-2.02E-2	-4.59E-3	-2.39E-2	4.22E-3	-
AET Condition: ~1.2 UV Suns at BPT = 80°-85°C								
ECIS-05	Glass	15295P	Glass	1.12E-2	-2.67E-3	7.86E-3	-9.53E-4	3.17E-4
ECIS-17	Glass	A9918P	Glass	4.98E-3	-2.72E-3	1.29E-3	-1.87E-3	1.86E-3
AET Condition: ~6.5 UV Suns at BPT = 65°C								
BP-A4	Glass	15295P	TPT	-5.88E-3	-1.42E-3	-7.70E-3	-4.22E-3	2.23E-3
BP-B4	Glass	15295P	Glass	-3.95E-3	-1.42E-3	-4.99E-3	-3.29E-3	1.69E-3
BP-C4	Glass	NREL-V11	TPT	-2.90E-3	-4.82E-3	-7.85E-3	-2.07E-3	1.62E-3
BP-D4	Glass	A9918P	TPT	-4.99E-3	-1.22E-3	-6.50E-3	-1.08E-2	2.05E-2
AET Condition: ~7.5 UV Suns at BPT = 85°C								
ECIS-06	Glass	15295P	Glass	7.51E-3	-5.30E-4	6.82E-3	-2.05E-2	3.15E-2
ECIS-22	Glass	A9918P	Glass	3.34E-3	4.29E-3	4.41E-3	-1.07E-2	2.17E-2
AET Condition: ~9.0 UV Suns at BPT = 145°C								
ECIS-09	Glass	15295P	Glass	-1.49E-2	-2.68E-3	-1.80E-2	-4.66E-2	5.66E-2
ECIS-18	Glass	A9918P	Glass	-2.83E-2	1.88E-3	-2.90E-2	-4.07E-2	4.80E-2