Degradation of Monofacial Double Glass and Glass Backsheet Photovoltaic Modules with Multiple Packaging Combinations

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Abstract—The long-term reliability of photovoltaic (PV) modules is essential to decrease the levelized cost of electricity and is dependent on module packaging choices. In this paper, we study the degradation of double glass (DG) and glass-backsheet (GB) PV modules with ethylene-vinyl acetate (EVA) and polyolefin elastomer (POE) encapsulants using multicrystalline PERC cells under accelerated exposures including modified damp heat (mDH) and mDH with full-spectrum light (FSL). The results showed that the modules with opaque rear encapsulant have greater power loss on average than those with UV-cutoff rear encapsulant for each module type. The dominant degradation mechanism was series resistance ($R_s$) increase indicating interconnect corrosion for most module types. In addition to the increased $R_s$, GB modules with UV-cutoff rear encapsulant experienced power loss by transmission loss, and the POE-GB type under mDH+FSL also had more cell shunting. For modules with opaque rear encapsulant, the POE-DG type under mDH+FSL had power loss dominated by transmission loss.

Index Terms—double glass, glass-backsheet, POE, EVA, PERC

I. INTRODUCTION

As a rapidly developing renewable and clean energy technology, the worldwide growth of photovoltaics (PV) installation has been close to exponential from 2000 to 2017 [1]. In 2019, more solar energy was added than fossil fuel and nuclear power generation capacities combined, and solar energy produced nearly twice as much power as wind and more than all other renewable energy sources together [1]. The immense market potential for solar energy is due to its natural advantages and the continually improving cost-competitiveness. Cell efficiency and long-term reliability are keys to reducing the energy cost. The passivated emitter and rear cell (PERC) beat the standard aluminum back surface field cell (Al-BSF) and became the dominant cell type since 2019 due to its higher cell efficiency and similar costs [1], [2]. Different module architectures and encapsulant materials are essential to determine the module lifetime. The primary purposes of the encapsulating material are to provide structural support, optical coupling, electrical isolation, physical isolation/protection, and thermal conduction to keep the brittle silicon cell and circuit components away from hazardous or degrading environmental factors [3], [4]. Due to these demanding requirements and lower price, EVA is the most popular choice as encapsulant material over the years. But field surveys of PV modules exposed in different climates over the years revealed several problems regarding the EVA encapsulant [4], [5] such as yellowing and released acid. The advantages of being acid-free, having lower water vapor transmission rate, and higher volume resistivity against the potential induced degradation make POE a highly competitive substitute in the encapsulant market [5]. In addition, the emerging trend of bifacial PV cells brings more interest to double glass modules. However, there are limited studies comparing double glass and glass-backsheet modules using POE encapsulant with rigorous variable control [6]. Commercial modules of selected brands are more commonly used instead [7], [8], so there is no consensus on double glass module performance compared to glass-backsheet modules.

In this study, eight variants of four-cell research minimodules were fabricated by Canadian Solar Inc. with differences of module architectures and encapsulant materials, using p-type multicrystalline silicon monofacial and bifacial PERC cells. Module architectures include double glass (DG) and glass-backsheet (GB) modules. Encapsulant materials are EVA or POE. The rear side encapsulant is the UV-cutoff type for set#1 minimodules and the opaque type for set#2 minimodules, from two suppliers. Set#1 minimodules use monofacial PERC cells, while set#2 minimodules use bifacial PERC cells, both supplied by Canadian Solar Inc. The minimodules were exposed...
to two accelerated exposures: modified damp heat (mDH) and the sequential exposure of modified damp heat with full-spectrum light (mDH+FSL). Step-wise characterizations and analysis were applied to each cell in the fabricated minimodule including current-voltage (I-V) curves under multiple irradiance levels and Suns-\textit{V}_{oc} curves. The results showed that modules with the opaque rear encapsulant have more average power loss than those with the UV-cutoff rear encapsulant for each module type. The dominant degradation mechanism was the series resistance \( R_s \) increase indicating interconnect corrosion for both accelerated exposures. However, in addition to the increased \( R_s \), GB modules with the UV-cutoff rear encapsulant had significantly greater transmission loss, and the POE_GB type also had significantly more cell shunting. Moreover, POE_DG modules with the opaque rear encapsulant had significantly greater transmission loss than other module variants under the accelerated exposure of mDH+FSL.

II. EXPERIMENTS AND METHODS

This section includes descriptions of fabricated minimodules, both kinds of laboratory accelerated exposures, characterizations, and corresponding analysis methods.

A. Research Minimodules

The research samples used in the study are four-cell research minimodules fabricated by Canadian Solar Inc. shown in Fig. 1. These four cells in one minimodule are connected in series, with five junction boxes installed on the backside to enable the electrical measurement of each cell in the laminated minimodule. There are four types of minimodules: EVA_GB, EVA_DG, POE_GB, and POE_DG, considering both encapsulant and module architecture choices. With set#1 using the UV-cutoff rear encapsulant and monofacial PERC cells, and set#2 using the opaque rear encapsulant and bifacial PERC cells, the four module types further form eight variants considering the set number, encapsulant material, and module architecture.

The glass of DG types is heat-strengthened 2.5mm glass for both sides, and that of GB types is tempered 3.2mm glass. The backsheet used in the GB types minimodules is the coating/PET/PVDF backsheet supplied by Cybrid. Two minimodules of each variant were exposed under each laboratory accelerated exposure, so there were eight cell-level measurements at each measurement step.

B. Laboratory Accelerated Exposures

The two indoor accelerated exposures are modified damp heat (mDH) and mDH with full-spectrum light (mDH+FSL). The conditions of mDH are 80 °C and 85% relative humidity. Compared to the standard damp heat, we lower the temperature by 5 °C to avoid over accelerating the hydrolysis of PET in the backsheet [5], [9] and bring a more fair comparison between DG and GB modules. The exposure time for each step is 504 hours (21 days), with a baseline plus five steps for the measurement, so the total exposure time is 2520 hours. To see the combined effects of the high temperature and humidity on an operated PV module, we designed an additional accelerated exposure of mDH+FSL. The exposure time for each step in mDH+FSL is also 504 hours (21 days), with the mDH taking 336 hours (14 days) and the FSL taking 168 hours (7 days). There are five exposure steps in total, so the total exposure time is also 2520 hours. The module temperature is controlled under 70 °C and 85 °C, the average irradiance is 420.4 W/m² and 85.1 W/m² for the front and back side, respectively. It's worth mentioning that our full-spectrum light contains very limited UV-light, the irradiance in TUV range from 300nm to 400nm for the front side and backside is 6.68W/m² and 5.21W/m², which is only around 10% compared to the MAST testing conditions designed for testing the reliability of backsheet [10]. The primary purpose of the FSL exposure is to have the PV modules fully operational, with current flowing. While modules are under FSL, 0.5 Ω load resistors were connected to hold the module voltage near that of the maximum power point \( P_{mp} \).

C. Characterizations and Analysis Methods

At each step, we measured the current-voltage (I-V) curves with Eternalsun Spire and Suns-\textit{V}_{oc} curves with Sinton Stage for each cell in the minimodule. The I-V curves were measured at three irradiance levels (1000 W/m², 500 W/m², and 250 W/m²) at room temperature. An example of multiple irradiance I-V curves for one cell in the fabricated research minimodule is shown in Fig. 2. A temperature correction and series resistance \( R_{s,IV} \) calculation using all three irradiance I-V curves for one cell in the fabricated research minimodule is worth mentioning that our full-spectrum light contains very limited UV-light, the irradiance in TUV range from 300nm to 400nm. The pseudo \( V_{mp} \) curve can be converted into the pseudo \( I-V \) curve by the \textit{ddiv} algorithm [11], [12].

\( Suns-\textit{V}_{oc} \) measures the open circuit voltages at varying irradiance. Taking the short-circuit current \( I_{sc,IV} \) from the 1 Sun \( I-V \) curve, the \( Suns-\textit{V}_{oc} \) curve can be converted into the pseudo \( I-V \) curve shown as the blue line in Fig. 3a [13]. Since the pseudo \( I-V \) curve is measured at open-circuit operation mode, it is not influenced by the series resistance in the \( R_s \) within the electrical circuit. The \textit{ddiv} algorithm [11] was used to extract the pseudo \( I-V \) features from the pseudo \( I-V \) curves also, including the \( P_{mp,IV} \) and the voltage at maximum power \( V_{mp,IV} \). The difference in \( P_{mp} \) between the 1 Sun

![Fig. 1: The front side and backside appearances of one research double glass minimodule.](image)
Fig. 2: Cell I-V curves at three irradiance levels.

I-V curve and the pseudo I-V curve is the power loss due to $R_s$ for each cell [13]. If the thickness and area of the solar cell are known, the relationship between the effective lifetime ($\tau$) and the minority-carrier density ($MCD$) can be deduced as shown in Fig. 3b [13], which is a quantitative measure for the recombination behavior.

Fig. 3: Example of curves developed from the $S_{uns-V_{oc}}$ measurement.

III. RESULTS AND DISCUSSIONS

In this section, we first discuss the power loss of eight variants of minimodules under both accelerated exposures and then investigate the degradation mechanisms contributing to the power loss. Four major degradation mechanisms are investigated including corrosion, transmission loss, and ohmic (cell shunting) and non-ohmic recombination.

A. Power Loss

Fig. 4 shows the 83.4% confidence intervals (CIs) for the normalized $P_{mp,IV}$ after exposure, which is calculated by the value of the last step divided by that from the same cell before exposure, for each module variant. The y-axis shows the module variant information, which includes the set number, encapsulant material, and module architecture. The confidence interval of #1_Control and #2_Control is evaluated from two control modules, which were retained for tracking the shift caused by the equipment for the step-wise measurement of each set. They are measured at each step with the exposed minimodules. We used the 83.4% CI because the boundary touching indicates a p-value around 0.05 in the two sample means t-test [14].

Comparing set#1 and set#2, set#2 has greater average power loss for all module types. Set#1 minimodules used UV-cutoff rear side encapsulants and mono-facial PERC cells, while set#2 minimodules used opaque rear side encapsulants and bifacial PERC cells. Even the minimum of this difference in the average value of the same module type between the two sets (1.3%) is larger than the difference in average values of the control modules between the two sets (0.93%). The EVA_GB modules suffered significantly more power loss than other set#2 minimodules under both accelerated exposures, but particularly in mDH. The other three module types in set#2 performed worse under mDH+FSL than mDH. Since our monofacial and bifacial PERC cells were supplied with very consistent processing technologies and the same wafer source, we believe the rear side encapsulant is more likely to cause the power loss differences between sets than the cell type.

For set#1 modules using the UV-cutoff rear encapsulant and monofacial PERC cells, there is no significant difference in the power loss among four module types, but the POE_GB type has greater average power loss in both accelerated exposures, which are 1.7% and 1.8% greater than that of the POE_DG type for mDH and mDH+FSL, respectively. However, for set#2 modules using the opaque rear encapsulant and bifacial PERC cells, the EVA_GB type has significantly greater power loss than all other three module types under mDH, POE_GB and EVA_DG module types under mDH+FSL. The power loss of the EVA_GB module type of set#2 is 6.7% and 3.2% greater than that of the EVA_DG type of the same set for mDH and mDH+FSL, respectively.

B. Degradation Mechanisms

Both accelerated exposures include high temperature and humidity conditions, which are generally believed to accelerate
The interconnect corrosion leads to an increase in series resistance $R_s$. The results of normalized $R_s$, which is extracted using all three irradiance level $I-V$ curves, after exposure for the eight module variants under both accelerated exposures, are presented in Fig. 5. Comparing to the control result of the two sets, all module variants experience increased $R_s$ on average. For set#1, the POE_GB type has the greatest increase in $R_s$ on average, which could explain its greater average power loss than other module types. For set#2, the EVA_GB type has the greatest increase in $R_s$ on average, and it is also the type that has the greatest power loss. The relative positions of these confidence intervals in the $nR_{s,IV}$ results are exactly opposite of those in the $nP_{mp,IV}$ results shown in Fig. 4, indicating the power loss for these eight module variants under both exposures are highly correlated to the degree of corrosion. In addition, the EVA_GB type has the least $R_s$ increase for set#1 but the greatest $R_s$ increase for set#2 indicating the additives in opaque encapsulants used in the study are likely to cause more corrosion.

The $P_{mp,PIV}$ indicates the $P_{mp}$ of the cell after removing the influence of $R_s$. By comparing the results obtained from $P_{mp,IV}$ and $P_{mp,PIV}$, we can infer the power loss contributed from corrosion. The $nP_{mp,PIV}$ results after accelerated exposures of the eight module variants are shown in Fig. 6. After removing the influence of $R_s$, there is very little remaining power loss which can be observed from the difference in scale of the x-axis in Fig. 6 and Fig. 4. Only the EVA_GB type of set#1 under both accelerated exposures, and the POE_GB type of set#1 and the POE_DG type of set#2 under mDH+FSL have remaining power loss of more than 0.5%. Comparing Fig. 4 and Fig. 6, corrosion contributes 76% of the power loss for the POE_GB type of set#1 and 89% of the power loss for the POE_DG type of set#2 under mDH+FSL, and 43% and 39% of the power loss for the EVA_GB type of set#1 under mDH and mDH+FSL, respectively. There is no doubt that corrosion dominates power loss for module variants except
the EVA_GB type of set#1 under both accelerated exposures. Properties related to other degradation mechanisms may vary, but their contributions to power loss are minimal for most module variants. Next, we investigate degradation mechanisms contributing to the remaining power loss for these four cases with more than 0.5% remaining power loss.

**Fig. 6:** The 83.4% confidence interval of $nP_{mp,PIV}$ after exposure.

Here, we use $nI_{sc,IV}$ to indicate the change in the transmission. The results of $nI_{sc,IV}$ of the eight module variants after exposure are shown in Fig. 7. Both results from control modules have average values significantly higher than 1 at the confidence level of 5% using one sample mean t-test. This shift in $I_{sc}$ of the control modules is caused by the drift in the measurement equipment with time due to the step-wise measurements instead of changes in the testing module. This $I_{sc}$ increase is likely to be the reason for $nP_{mp,PIV}$ to be significantly greater than that of the control modules for some variants after exposure, such as the POE_DG and the EVA_DG of set#1. (Pseudo I-V curves use $I_{sc}$ extracted from $I-V$ curves as input for the exposed module, but the $I_{sc}$ used for control modules to obtain $Suns$-$V_{oc}$ related results is a constant.) For set#1, the EVA_GB type under both accelerated exposures and the POE_GB type under mDH+FSL have significantly greater $I_{sc}$ decrease than the other two DG module types under the same exposure, and the control of set#1. For set#2 modules, the POE_DG type under mDH+FSL also has a comparable change in $nI_{max}$ compared to the other three module types. So recombination is unlikely to be the contributor for their remaining power loss after removing the influence of $R_s$.

**Fig. 7:** The 83.4% confidence interval of $nI_{sc,IV}$ after exposure.

The last degradation mechanism considered is cell shunting, which is also called ohmic recombination. Here we use the shunt resistance $R_{sh}$ extracted from the 1 Sun $I-V$ curve as the indicator for this type of degradation. The results of $nR_{sh,IV}$ for the eight module variants after exposure are shown in Fig. 9. Shunt resistance ($R_{sh}$) is tough to extract accurately from $I-V$ curves due to its reciprocal relationship with the slope near $I_{sc}$, but by comparing different types of modules, we can see some differences in results. For set#1 modules, only the POE_GB type has significantly greater decrease in $nR_{sh,IV}$ than the control. However, the two DG module types have more positive $nR_{sh,IV}$ after exposure, which are significantly higher than that of the two GB module types. We believe the differences compared to the EVA_DG and POE_DG types for both accelerated exposures. The POE_GB type shows the smallest decrease in $nR_{sh,IV}$ after mDH+FSL exposure for all set#1 modules. For set#2 modules, the POE_DG type under mDH+FSL also has a comparable change in $nR_{sh,IV}$ compared to the other three module types. So recombination is unlikely to be the contributor for their remaining power loss after removing the influence of $R_s$.

**Fig. 8:** The 83.4% confidence interval of $n\tau_{max}$ after exposure.

The maximum effective lifetime ($\tau_{max}$) extracted from the curve of effective lifetime versus minority carrier density is used for evaluating the recombination behavior in cells. A longer effective lifetime is preferred for higher cell efficiency. This recombination behavior includes both the ohmic and non-ohmic types, where the ohmic type is cell shunting. The results of the $n\tau_{max}$ of the eight module variants after exposure is shown in Fig. 8. For set#1 modules, only the POE_GB type has significantly greater decrease in $n\tau_{max}$ after exposure of the EVA_GB type is lower than that of the other module types, but the average has no significant
decreased $R_{sh}$ could contribute to the non-corrosion power loss for the POE_G type of set#1 under mDH+FSL, but the reason for shunting change differences between DG and GB modules of set#1 is unclear. For set#2 modules, the POE_DG type under mDH+FSL has the least decrease in $n_R_{sh,IIV}$, so shunting does not contribute to its power loss. Compared to the results from control modules, we observed a decrease in $n_R_{sh,IIV}$ for some set#2 module types under each accelerated exposure, but as discussed before, these changes do not lead to any considerable loss in power.

![Fig. 9: The 83.4% confidence interval of $n_R_{sh,IIV}$ after exposure.](image)

### IV. Conclusions

In this paper, we quantified power loss and identified dominant and secondary degradation mechanisms contributing to any considerable loss in power (larger than 0.5%) for a variety of module architectures and materials through modified damp heat exposures with and without full spectrum light. For these four module types including the POE_GB, POE_DG, EVA_GB, and EVA_DG of two sets, where set#1 uses the UV-cutoff rear encapsulant and monofacial PERC cells, and set#2 uses the opaque rear encapsulant and bifacial PERC cells, the EVA_GB of set#2 has the greatest power loss, which is significantly greater than all other module combinations under mDH, and most module types under mDH+FSL. Set#2 modules have greater average power loss than set#1 for every module type. The dominant degradation mechanism for module variants except the EVA_GB type of set#1 under both accelerated exposures of mDH and mDH+FSL is corrosion. There are four cases that have considerable remaining power loss after removing the influence of series resistance. They are the EVA_GB type of set#1 under both accelerated exposures, the POE_GB type of set#1, and the POE_DG of set#2 under mDH+FSL. Significantly greater transmission loss is the contributor to their remaining power loss, and cell shunting could be an additional contributor for the POE_GB type of set#1 under mDH+FSL.

### REFERENCES


