DuraMAT
Durable Module Materials Consortium

Discover, Develop, and De-Risk module materials, architectures, accelerated testing protocols,data analytics, and financial models to reduce the LCOE of solar energy

MODULE-LEVEL SOLUTIONS FOR DEGRADATION BY IONIZATION DAMAGE

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DuraMAT Capabilities

1. Data Management & Analytics, DuraMAT Data Hub
2. Predictive Simulation
3. Advanced Characterization & Forensics
4. Module Testing: Module Prototyping and Combined-Accelerated Stress Testing (C-AST)
5. Field Deployment
6. Techno-Economic Analysis

Capability Goals

Degradation processes involving damage from UV radiation and/or ion-related damage from positive high-voltage bias of the encapsulation and cell/encapsulant interface will be characterized, mechanisms will be clarified, degradation models and rate equations will be developed, and the value proposition of various packaging-based solutions will be quantified.

Accomplishments

From the start of the project (October 1, 2018) we:
- Tested Si cell types with n^+ and p^+ front surfaces and with silicon oxide, nitride, amorphous silicon, poly-silicon and aluminum oxide passivation to screen sensitivity to UV light
- Analyzed the cell/EVA and EVA/glass interfaces of MiMo under positive-bias ionization test to probe the ion migration and material chemistry behind the degradation

Outcomes and Impact

The properties of polymer packaging materials required to mitigate module power degradation will be identified. Material properties and performance models will be entered into the DuraMAT DataHub. With this, we will inform the PV module value chain how degradation rates can be minimized for a 50-year module life along with the corresponding valuation of degradation and preventative packaging materials.

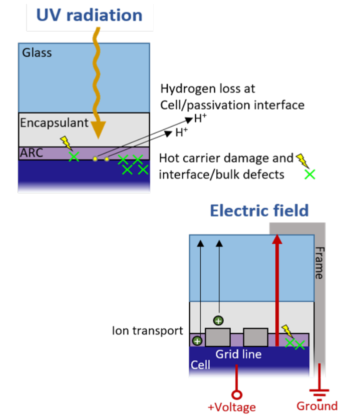
Motivation

After years of improving module efficiency while targeting mean degradation rates of 0.5 to 0.6 %/y for crystalline silicon technology, there is much evidence that the degradation rates are now increasing significantly. Contributing factors include:

- Radiation damage (UV-Light Induced Degradation):
  - Trina solar: -4.5%/y degradation rate in Singapore
  - DOE National Laboratory Regional Test Centers showed degradation of -1 % ≤ r ≤ -2%/y in crystalline silicon modules.
  - Jinko Solar: -4% ≤ r ≤ -7% efficiency loss from 540 MJ·m^{-2} of UV-A light
  - ISFH: 15% relative power loss during of 1.8 GJ·m^{-2} UV exposure, attributed to H^+
- Electrical bias from positive system voltage (e.g., +1000 V, +1500 V) can drive ions and metallization through the encapsulation.
  - NREL: Ion transport can affect the cell passivation, resulting in power loss of 5% to 40% in p-PERC+ (bifacial)
  - NREL: Damage at cell rear with up to 17% power at cell fronts in n-PERT modules

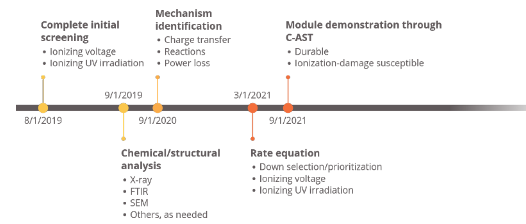
Delamination can also occur due to cell surface reactions driven by light and bias.

Ionization Damage Mechanisms



Scope and Timeline

- Quantify and characterize the effects of UV- and voltage-induced damage in various modern commercial cell types to identify samples of interest
- Control the degradation rate by varying the UV cut-on wavelength to the cell
- Characterization of the degradation processes including ion migration to understand the degradation and ensure its prevention
- Identify polymer packaging materials to mitigate module power degradation
- Enter results into the DuraMAT DataHub and inform the value chain how to minimize degradation rates for a 50-year life and value degradation prevention



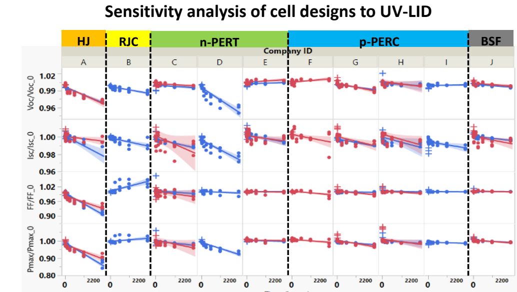
UV Light Screening Test

Cell technology	Company ID	Front structure	Rear structure	NREL FO	NREL BO	SLAC FO	SLAC BO	SLAC FS
HJ	A	ITO/(p-)a-Si/(i)a-Si	n Si/(i)a-Si/(n+)a-Si/ITO	3	-	3	3	2
RJC	B	SiNx/SiO2/n-Si	-	3	3	-	-	-
n-PERT	C	SiNx/AlOx/p+Si/n Si	n Si/n+Si/SiNx	3	-	3	3	3
	D	SiNx/SiO2/p+Si/n Si	-	3	-	-	-	-
	E	SiNx/SiO2/p+Si/n Si	n Si/n+Si/SiNx	3	-	3	3	2
	F	SiNx/SiO2/p+Si/n Si	-	-	-	3	-	-
p-PERC	G	SiNx/SiO2/p+Si/n Si	p Si/AlOx/SiNx	3	-	3	3	3
	H	SiNx/n-Si/p Si	p-Si/SiNx	3	-	3	3	-
	I	SiNx/n-Si/p Si	-	3	-	-	-	-
BSF	J	SiNx/n-Si/p Si	-	3	-	3	-	-
RJC		SiNx/SiO2/n-Si		Control		-		
p-PERC		SiNx/n-Si/p Si		-		Control 1		
BSF		SiNx/n-Si/p Si		-		Control 2		

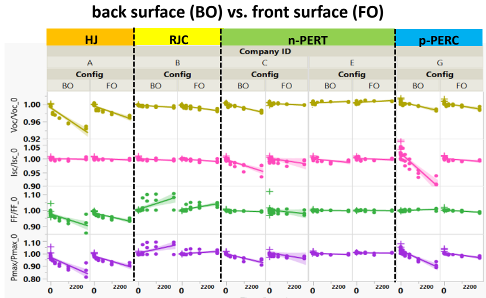
- 2000 h UV dose in chamber ≈ 2 y outdoor exposure in Miami or Phoenix, USA (295 ≤ λ ≤ 380 nm).
- Screening of sensitivities of various cell makes to UV light show their potential to cause degradation
- Degradation rate ≥ -0.5 %/y (equivalent) is common.
  - Heterojunction (HJ) was found to be the most susceptible cell structure to UV degradation, followed by rear junction cells (RJC), n-PERT and p-PERC. The conventional BSF cells exhibited higher resistance to UV-LID.
  - The back surface of bifacial cells was found to be more prone to UV-LID than the front surface owing to difference in passivation layer.

*Abstract is submitted at IEEE PVSC, 2020

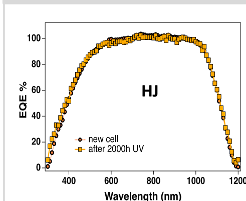
Sensitivity analysis of cell designs to UV-LID

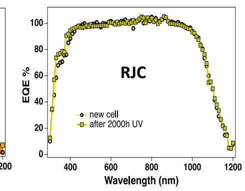


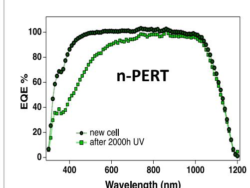
Comparison of UV-LID in cells when irradiated from back surface (BO) vs. front surface (FO)



EQE Characterization of UV-LID





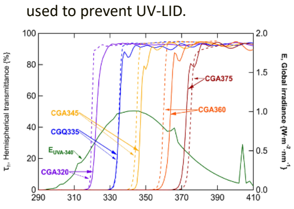


Comparison of EQE for three of the most affected cell makes from screen test between unaged and weathered (8.9 MJ·m^{-2} at 340 nm, 2000 h UV) specimens.

- Loss of EQE performance in UV-Vis and NIR (near bandgap) observed in literature for UV-LID.
- EQE of weathered n-PERT cell shows decreased performance at λ < 700nm.
- No change in EQE of HJ and RJC cells from screen test.
- Additional characterization (reflectivity, SIMS) and failure analysis (XPS/Auger) of cells is ongoing.

UV Filtering to Reduce UV-LID

- Degradation in the screen test results from UV irradiation, but the threshold damaging wavelength is not agreed upon in the literature.
- A series of five filters will be used similar to the ASTM G178 method to verify the wavelengths contributing to damage.
- From the results, custom encapsulant formulations will be applied in the next round of study to demonstrate new materials that may be used to prevent UV-LID.

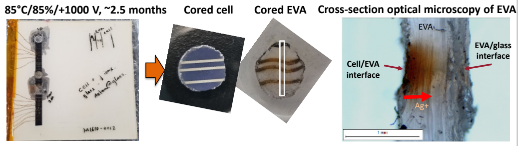


Transmittance spectra, including NREL-verified (solid lines) and manufacturer's catalog data (dashed lines), for the sharp cut-on filters that will be used in the second round of study.

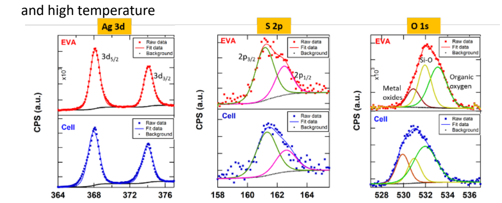
Comparison of UV intensity (for 295 ≤λ ≤ 360 nm, for UVA-340 lamp) for components and laminates used in PV modules, based on analysis of reflectance at interfaces and material absorptance.

MATERIAL STACK	INTENSITY {W·m^{-2}}	INTENSITY FACTOR
bare cell	48.5	1.0
silica	44.9	1.1
AR + textured glass	38.0	1.3
J: POE-1 (UV blocking)	2.6	18.8
A: POE-2 (UV transmitting)	41.8	1.2
silica/J: POE-1/Si_xN_y	1.8	26.6
silica/A: POE-2/SixNy	29.2	1.7
AR + textured/J: POE-1/SixNy	1.7	29.3
AR + textured/A: POE-2/SixNy	24.9	1.9

Positive Bias Voltage Degradation



- Migration of Ag+ into EVA from cell grid observed. No signature of Ag at EVA/glass interface, evident from optical imaging and XPS depth profiling
- XPS results indicated that Ag_2S and/or Ag_2O are likely responsible for brown discoloration of EVA --> I_{sc} loss
- Sulfur is diffused into the module from the ambient air, facilitated by moisture and high temperature



*An abstract is submitted at IEEE PVSC, 2020 and a journal manuscript is under preparation

DuraMAT Network Engagement

The DuraMAT capabilities:

Modules forensics: Chemical and structural analysis of interfaces to examine the photo-electro-chemical degradation effects

Accelerated testing & module prototyping: Mini-module fabrication and testing under UV or positive bias conditions

Predictive simulation: Through application of models developed in this work

Outdoor testing: For materials studies, experimental and reference modules

Applied data analytics: With the DataHub for data tools to model designing, testing, and manufacturing procedures that can be used to forecast performance and durability

SLAC visit to NREL April 2019:
- Module coring
- Soldering tutorials
- Project planning

Industry outreach:
- Frequent engagement with Brian Habersberger from Dow
- General guidance to the project directions
- Characterization (laser ablation mass spec)
- Materials

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