Impact of moisture ingress in PV modules on long-term performance: the role of EVA formulation, module design and climate

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From basics to industrialization

Cells and coatings, > 22% HJT, modules, BIPV, PV systems and storage
Modules

- Module reliability testing and modeling
- Module components and materials accelerated reliability testing
- Module testing tools (encapsulation quality and reliability)
- Participation in work groups for PV standards development

Applied research, industrial mandates

- New PV module encapsulation materials (formulation and extrusion) and interconnection techniques
- Process development
- Innovative module design
- Architectural projects with PV System
- Integration to grid, storage
Tools developed for properties assessment

- Testing tools development
  - EVA gel content determination [1, 2]

By DSC

[2] Li, H.-Y., et al. (2014), Submitted

By optical

- Adhesion testing method [3]
Impact of encapsulation process on modules

- Encapsulation process study

➢ Effect of cooling press [1, 2]

Residual stress reduction

Peeling strength enhancement

Haze reduction

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Impact of encapsulation process on modules

- Encapsulation process study

  Voids evolution [1]

  ✓ Possible origins of voids formation during EVA module encapsulation:

  • Residual solvent in EVA film;
  • Volatile produced by soldering flux;
  • Dehydration reaction between silane primer and the glass surface;
  • Surface contaminations (EVA, glass, cell, backsheet, etc.);
  • EVA volumetric shrinking
  • Volatile organic compounds (VOCs) produced from the EVA curing reactions
  • Wet air dissolved in EVA

[1] Li, H.-Y., et al. (2014), Accepted in Polym-Polym Comp.
Linking encapsulation quality to reliability

Encapsulation Materials/Design

Encapsulation Quality:
- Gel content
- Adhesion
- Voids
- Cell cracking
- Cell swimming
- Residual stress
- Remaining amount of additives

Module Reliability in ALT:
- Damp heat
- Humidity freeze
- Thermal cycling
- Mechanical loading
- Hail test
- UV radiation
- Electrical insulation
- PID
- ...

Simulated
Predict
Module reliability in field deployment

Open questions:
1. Quality vs. Module reliability
2. Module life time prediction

[1] Li, H.-Y., et al. (2014), Submitted
Impact of technology on materials choice

• New encapsulation materials and interconnection

➢ SmartWire Connection Technology in collaboration with Meyer Burger AG [1]

➢ New encapsulant materials[2]

Encapsulant selection based on the viscosity profiles

Moisture ingress into PV modules

- Why moisture ingress important for module reliability?
  - Delamination (mechanical stability loss, optical loss, water accumulation, ...)
  - Corrosion (Rs increase, could accelerate EVA yellowing, ...)
  - Enhanced probability of PID (due to reduced volume resistivity of encapsulants)
  - Encapsulant degradation (in combination with heat and UV)
  - ...

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EVA – most criticized problem: Degradation

Degradation under UV and/or Heat

Degradation under DH+Heat

2 major consequences of EVA degradation: yellowing and acetic acid production
Moisture ingress into PV modules

- Approaches to studying moisture ingress used in our lab

<table>
<thead>
<tr>
<th>Technique</th>
<th>Experiment</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permeation</td>
<td>WVTR Mocon</td>
<td>WVTR &gt; $10^{-3}$ g/d/m²</td>
</tr>
<tr>
<td>Capacitance embedded sensor</td>
<td>Monitoring</td>
<td>Sensor must be embedded Long term drifts T &lt; 70°C</td>
</tr>
<tr>
<td>FTIR</td>
<td>Fingerprint of bound water in IR spectrum</td>
<td>No peak overlap in water region needed (ideal for PVB) Transparent samples</td>
</tr>
<tr>
<td>DVS</td>
<td>Dynamic vapor sorption</td>
<td>Only bulk materials, no multilayers</td>
</tr>
<tr>
<td>Ca spot</td>
<td>Ca oxidation experiment</td>
<td>For very low WVTR, qualitative test</td>
</tr>
<tr>
<td>FEM</td>
<td>COMSOL simulation</td>
<td>Materials properties must be known</td>
</tr>
</tbody>
</table>
Moisture ingress into PV modules

- Comparison on different approaches

![Arrhenius plot for diffusion coefficient (EVA-water system)](image)

- Good agreement achieved!
Moisture ingress into PV modules - Modeling

- Acquire input material properties – WVTR measurement
  - WVTR characterisation of different commercial backsheets (BS) and EVAs formulations: Measured with Mocon Permatran 3/33 at 30°C, 40°C, 50°C
  - Measured and calculated units
    \[ \text{WVTR}(t, T) \rightarrow \text{measured} \]
    \[ \text{Diffusion coefficient } D(T) \text{ nd Water solubility in polymer } S(T) \rightarrow \text{calculated} \]

\[
WVTR(t \rightarrow \infty) = -D \cdot S \cdot \frac{p_{H_2O}^{\text{dry}} - p_{H_2O}^{\text{wet}}}{L}
\]

\[
WVTR(t, T) = WVTR(t \rightarrow \infty, T)(1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp\left(\frac{-D \cdot n^2 \cdot t}{L^2}\right))
\]
Moisture ingress into PV modules

- Acquire input material properties – WVTR data treatment

  WVTR data fitting

  T-dependency of D

  $E_a = 46.56 \text{ kJ/mol}$

- Temperature dependency of WVTR, D and S
- Determination of activation energy $E_a$ for D and S

$\rightarrow$ With these, moisture ingress can be modeled in FEM.
Moisture ingress into PV modules - Modeling

- 2D FEM modeling geometry

A FEM model was built in COMSOL to compute solutions of equation:

$$\frac{\partial c(\vec{x}, t)}{\partial t} - \text{div} \left( D \cdot \text{grad} c(\vec{x}, t) \right) = 0$$

Glass/Glass

Glass/Back Sheet
Moisture ingress into PV modules - Modeling

- Three climates under study

<table>
<thead>
<tr>
<th>Climatic zone</th>
<th>“Cool &amp; Humid”</th>
<th>“Hot &amp; Humid”</th>
<th>“Hot &amp; Dry”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Neuchâtel (Switzerland)</td>
<td>Mumbai (India)</td>
<td>Sharurah (Saudi Arabia)</td>
</tr>
</tbody>
</table>

Module temperature was estimated using King’s model
Open-rack mounting configuration considered.
Moisture ingress into PV modules - Modeling

- Different climates

Glass/breathable Back Sheet module (G/BS), with EVA1 encapsulant, simulated for 1 year.

- Cool & humid
- Tropical
- Desert

- At cell front: water accumulation rises gradually, as controlled by the climates and moisture diffusion through encapsulant.

- At cell back: water concentration evolves with ambient relative humidity, as dominated by the permeation through BS.
Moisture ingress into PV modules - Modeling

- **Different climates**

Glass/breathable Back Sheet module (G/BS), with EVA1 encapsulant, simulated for 1 year.

- **Cool & humid**

  In Neuchatell and Mumbai, water concentration exceeds saturation concentration in EVA on the cell back.
  - Leading to water condensation => potential corrosion occurs
  - While in Sharurah, always stay below saturation concentration.
Moisture ingress into PV modules - Modeling

- Different climates

Glass/Glass module (G/G), with EVA1 encapsulant, simulated for 1 year.

Cool & humid

- In desert climate $C_{\text{water}}$ at module edge quickly reaches a stable value: a result of higher $T$ and low RH%.
- In all 3 climates, $C_{\text{water}}$ is far from saturation level after 1 year of exposure.
- Moisture ingress is fastest in tropical climate with both high $T$ and high RH%.
Moisture ingress into PV modules - Modeling

- Different module configuration: hermetic (G/G) v.s. breathable (G/BS)

**Tropical**

- Both climates: In G/BS, moisture fully loaded at cell back after 1st year;
- Both climates: G/G configuration reduces greatly the moisture accumulation;
- Breathable configuration cannot breathe out moisture effectively in cool+dry season

**Desert**

- Both climates: In G/BS, moisture fully loaded at cell back after 1st year;
Moisture ingress into PV modules - Modeling

- Different encapsulants in Neuchatel

Glass/Glass module (G/G) with 3 types of encapsulants, simulated for 1 year.

<table>
<thead>
<tr>
<th>Encapsulant</th>
<th>WVTR (steady-state) [g/m²/s]</th>
<th>$E_a$ [kJ/mol]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$30^\circ C$</td>
<td>$40^\circ C$</td>
</tr>
<tr>
<td>EVA 1</td>
<td>7.2E-05</td>
<td>14E-05</td>
</tr>
<tr>
<td>EVA 2</td>
<td>12E-05</td>
<td>16E-05</td>
</tr>
<tr>
<td>PO 1</td>
<td>7.5E-06</td>
<td>2.0E-05</td>
</tr>
</tbody>
</table>

- PO#1, a commercial polyolefin-based encapsulant, showed significantly lower moisture ingress than the other 2 EVA encapsulants in one year.
- EVA#1 reduced the water concentration by over 50% compared to EVA#2 — EVA formulation plays an important role on WVTR(T).
Example of link between moisture and reliability

- Different encapsulants in extended damp heat [1]

Standard solar cells, breathable module configuration, 85 °C / 85% RH, 8000 h.

Reason for higher degradation rate of EVA in DH:
- Higher water concentration
- Higher hydrothermal degradation
- Acetic acid production
- Higher corrosion rate at metallic surface

Reliability

Conclusion

- EVA formulation and climate controls moisture ingress
- Climate+UV+ moisture controls “EVA degradation”
- EVA degradation +cells/interconnections controls (part of module) degradation

- Predictive simulation of failure in the field requires multi-physics model
  Or
- empirical accelerated aging approach (with no insight into microscopic phenomena)
One way to reduce operating temperature (and moisture)...

- What if modules were White?

  ➢ Solar cells designed to maximize light absorption → Dark appearance (Ideally black)

  ➢ White color in architecture is important:

  ![Fresh](image1) ![Elegant](image2) ![Fits to any architectural style](image3)

![CSEM has successfully developed the 1\textsuperscript{st} white PV module worldwide!!][1]

White photovoltaic modules

How does it work

colored film made with innovative nano-technology

highly efficient solar module
White photovoltaic modules

How does it work

sun light visible color

infrared rays

UV visible Infra-Red

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White photovoltaic modules

How does it look?
White photovoltaic modules

A new building material

- Better aesthetics
- Easiest integration
- Building façade are becoming active

➢ A new building material
White module

Reminder*:
CSEM White module

Lower module T

Reduced module thermal loss

Reduced moisture ingress and (hydro-)thermal degradation

Improved module reliability

*Study ongoing

Thanks!