The challenges in understanding CIGS thin film cell and module reliability

Rajalakshmi Sundaramoorthy
Dave Metacarpa, Jim Lloyd, and Pradeep Haldar
Discussion topics

- PVMC – Introduction

- **CIGS Device reliability**- Failure modes/Mechanisms
  - Device/Unit film metrology,, TCO engineering

- **Module level reliability**
  - Field failures- Failure modes
  - Indoor Accelerated Lifetime Tests
  - Select examples-Failure mechanisms
    - Combinatorial stress
    - Interconnect

- **System level failures**
  - Modeling

- **Integrated database**

- **Challenges and opportunities summarized**
The U.S. Photovoltaic Manufacturing Consortium – Program Overview

• Manufacturing scale research through industry led consortium for collaborative and proprietary activities at a pilot line and manufacturing development facility

• Overall investment of $300 M over 5 years from DOE, Industry, NY State.

• Focus on leading thin film solar PV technology – and manufacturing methods

• Expertise of primary partners – SEMATECH, CNSE – in consortium management, technology development, manufacturing productivity, and workforce development

• Breadth of support – partnership with ~60 companies and organizations throughout thin film PV industry supply chain
Strategic Objectives of PVMC

- Establishing Roadmaps and Standards
- Establishing Thin Film Manufacturing Development Facility
  - Access to 100 kW line
  - Front End and Back End of 10 MW
  - (Flexible and Rigid Line)
- Thin Film Manufacturing Scale-up
  - Best Practices and Cost Modeling
  - Productivity, Effectiveness and Manufacturing Quality
- Thin Film Commercialization Support
  - Deployment, Licensing, Attraction, Incubation
- Developing Highly Trained Workforce

TWG- Technical Working Groups

- LPV: Manufacturing scale up
  - Industry relevant projects (LPV)
- Metrology: Metrology for Manufacturing Performance measurement standards
- Field Performance: Bankability
  - Outdoor performance Monitoring
  - Indoor Accelerated Life time tests

SOLICIT INDUSTRY INPUTS
Design Projects
Results delivered according to milestones
# PVMC Multi-Year Strategy: 3 year and beyond

<table>
<thead>
<tr>
<th>Year</th>
<th>Partners</th>
<th>Objectives/Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>(FEOL)</em> PV Cell Manufacturing</td>
<td><strong>Yr1</strong></td>
<td>Equipment/Material, Metrology/Suppliers, R&amp;D Companies</td>
</tr>
<tr>
<td><em>(BEOL)</em> Module Manufacturing</td>
<td><strong>Yr2</strong></td>
<td>Equipment/Suppliers, PV and Roofing Manufacturers</td>
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<tr>
<td>Roof Integration</td>
<td><strong>Yr3</strong></td>
<td>Architects, Installers, Roofers, Contractors, Utilities</td>
</tr>
<tr>
<td>LPV Deployment</td>
<td><strong>Yr4</strong></td>
<td>Utilities, Installer, End Users, Building Owners</td>
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**PVMC**
Challenges in CIGS Reliability

To develop reliable PV modules
  Understand potential failure mechanisms driving a failure mode
  Reliability of a PV product depends on
    Manufacturing methods
    Types of packaging
      Flat panel (Glass-Glass)-Monolithic
      Glass/Backsheet
      Flexible modules (LPV)
      CPV
    Used condition (climates)

Observe failure modes (identify mechanisms) in outdoor PV field

Need to wait for 25 years – NOT a solution!

Develop accelerated stress tests-(and formulate Qualification tests)
  to observe the failure mechanisms in a short period of time
  to predict lifetime of the module
CIGS Device reliability
Associated Failure modes/Mechanisms
Device/Unit film metrology
TCO Engineering
CIGS device stack - Deposition methods and materials

In-depth analysis using different characterization techniques is required to understand the interfacial properties-Include Na incorporation
Device efficiency - Moisture and Temperature/Light Effects

1) CIS Device-Level Stability - D. Albin et.al
2) Influence of damp-heat in electrical, optical and morphological properties of encapsulated CIGS devices - R. Sundaramoorthy et.al.

37th IEEE-PVSC

Modeling of Dark and light JV curves

2) DH Degradation – Efficiency (0-50 hrs) - Encapsulated without EVA
- driven by decrease in $J_{sc}$ & FF >10%
- Less than 5% decrease in $V_{oc}$

Parameters from Dark JV
- No change in R series for the cells packaged in back sheet with glass

Parameters from Light JV
- Increase in R series for the cells packaged in back sheet with TEFZEL (high WVTR)

Series Resistance (ohms-cm$^2$) Diode Ideality Factor

Efficiency (%)

Damp heat in Dark

Glass

Tefzel

DH Exposure Hours (h)
Recombination and lifetime - correlation

PL image after re-fabrication of the DH exposed device

**Before DH**

**After DH**

PL- Dark spots indicate increased recombination after DH

Influence of damp-heat in electrical, optical and morphological properties of encapsulated CIGS devices - R. Sundaramoorthy et al. 37th IEEE-PVSC

TRPL measurements after DH exposure

<table>
<thead>
<tr>
<th>Back sheet</th>
<th>Lifetime $\tau_1$ (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A, stored in ambient</td>
<td>6.25</td>
</tr>
<tr>
<td>Glass</td>
<td>8</td>
</tr>
<tr>
<td>TPAT</td>
<td>8.56</td>
</tr>
<tr>
<td>TPT</td>
<td>8.87</td>
</tr>
<tr>
<td>Tefzel</td>
<td>1.85</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DH Exposure Time (h)</th>
<th>$V_{oc}$ (V)</th>
<th>$J_{sc}$ (mA/cm$^2$)</th>
<th>FF (%)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.69</td>
<td>32.8</td>
<td>78</td>
<td>17.7</td>
</tr>
<tr>
<td>1</td>
<td>0.64</td>
<td>28.1</td>
<td>58</td>
<td>10.4</td>
</tr>
<tr>
<td>784</td>
<td>0.65</td>
<td>19.9</td>
<td>59</td>
<td>7.6</td>
</tr>
<tr>
<td>N/A, after re-fabrication</td>
<td>0.56</td>
<td>28.4</td>
<td>60.9</td>
<td>9.68</td>
</tr>
</tbody>
</table>

JV parameters before and after DH exposure and re-fabrication indicate absorber is intact; while TCO has degraded.
Material level – Identification of failure mechanisms

Oxygen 1s core level peak for samples encapsulated in Tefzel - High WVTR and TPAT-Low WVTR.

Evidence of hydrolysis of ZnO (TCO) and moisture in TCO
Formation of Zn(OH)_2 after DH exposure and moisture trapped in the devices packaged with backsheet having high WVTR

(531.5–532.2 eV) Zn(OH)_2

(532.8–534 eV) adsorbed water

529.9–530.7 eV O 1s peak

One approach for CIGS devices for improving device performance in DH

- Alternative TCO which is DH stable IZO (InZnO) for CIGS
  - Conductive layer (i-ZnO/c-InZnO)
  - Bi-layer (i-InZnO/c-InZnO)

- Barrier layers on CIGS (TCOs and PTMO)

Un exposed  
After 38h in DH

PL Image after DH exposure

PTMO protects the CIGS device  
Extends the life time of the bare device- By how many hrs?  
How is it related to lifetime during outdoor exposure
Order of decreasing stability:
ITO ~ InZnO >> B:ZnO >>> Al:ZnO ~ BZO

1) R. Sundaramoorthy et al, SPIE 2010
2) Pern et al, SPIE 2011

Important properties of TCO for DH stability
- Thickness of the film, Sheet Rho
- Grain boundaries
- Bias conditions, (Processing parameters)
- Multi-layers of same or different films has profound effect on the stability of the TCO
Understand Long term reliability - CdS diffusion in CIGS failure mechanisms

- Failure physics correlated to mass transport kinetics
  - Diffusion via lattice (volume)
  - Diffusion via grain boundary
- SIMS analysis —
  - affected by Surface roughness
- Polish CIGS /Deposit CdS

LaClair’s analysis

\[
 s\delta D_b = 1.32 \left( \frac{D}{t} \right)^{1/2} \left( \frac{\partial \ln \bar{c}}{\partial Z} \right)^{6/5} \n^{-5/3}
\]

The activation energy for volume diffusion of cadmium in CIGS is \(\sim 1\) eV [2]
Thus \(\Delta E_b\) is \(\sim 0.7\) eV ; Equation necessarily suggests \(\Delta E_b > \frac{1}{2} \Delta E\)
Module level reliability
Field failures
Indoor Accelerated Lifetime Tests (ALT’s)
Interconnect reliability
Modeling
Different ways of fabricating CIGS

<table>
<thead>
<tr>
<th>Deposition method</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co-evaporation</td>
<td>Wurth, GSE, Ascent, Solibro</td>
</tr>
<tr>
<td>Selenization</td>
<td>Solar frontier, Avancis, STION, TSMC</td>
</tr>
<tr>
<td>Sputtering</td>
<td>Miasole</td>
</tr>
<tr>
<td>Nanoparticle</td>
<td>Nanosolar, ISET,-Pioneer products</td>
</tr>
<tr>
<td>Electroplating</td>
<td>Solopower/NEXCIS</td>
</tr>
<tr>
<td>FASST and other process</td>
<td>Heliovolt</td>
</tr>
</tbody>
</table>
In the process of manufacturing a PV module, each and every layer can be processed in different ways. Material and equipment suppliers come up with new products catering to different process steps. Combination of all these aspects makes the reliability of the product challenging.
Qualification testing is confused with reliability testing
Incorporates pass/fail criteria - DOES NOT PREDICT PRODUCT LIFE TIME
Stress levels and durations - limited - to minimize time and cost
Goal: significant # of modules will pass the criteria - Production modules will be built the same way test modules are built.
Where does the failure occur in TF-PV?

New generation modules (‘05-’07) - DH failure rate 70%

Lessons learnt (07-09):
• Brought down the DH failure rate down to 30%
• New failure modes observed.

Questions:
How do we replicate these failures in the lab?

Design differences in modules can lead to different types of failures in the field:

- **Hard failures** (-20% to -85%) Pmax change due to FF
- Substring failure: (Voc loss)
- Delamination (Isc loss)
- Cell related loss and non-cell related loss

- **Soft failures** (10 to -20% ) Pmax change due to FF

No dearth for interesting and useful topics to work on!
Indoor Accelerated Lifetime Tests

- Junction degradation
- Packaging
- Interconnect degradation
- Barrier layers

Need to establish
- Standard structure for a failure mechanism.
- ALT’s beyond normal acceleration-combinatorial tests
  - Chamber options ((DH/Dry) - with Light/ HALT/ HASS)
- Protocols for measurements (Combinatorial/Stress order/ Load/In-situ Normal Operating Cell Temperature (NOCT)/ Standard Testing Conditions (STC))
- Protocols for combinatorial stress factors (RH, T, Bias, Mechanical) + Pre conditioning)
Effect of light, temperature and moisture

Indoor: Light Soak after DH exposure for 1000hrs
Outdoor: Enhancement in efficiency by outdoor light soaking for 3-4 hrs after fabrication

Probable reason: Changes in the buffer layer due to the presence of moisture and heat could be the reason for decreased and improved performance the efficiency-failure mechanisms worth investigating

Indoor: DH exposure with and without light exposure
Degradation in the presence of light is less than degradation in Dark—Damp heat

Humidity freeze and Temperature cycles with no humidity shows similar changes in performance.

Future experiments
Isolate Temp. and Moisture and perform indoor tests with and without light to understand electrical performance and compare the results with outdoor performance
Indoor ALT’s – Stress conditions- Multiple failure modes

Temperature and Humidity effects

Combinations of different T and RH

Multiple failure modes
High temperature : CIGS failure
Low Temperatures : ECA dominated Failures

Need to interpolate the results to use condition
D.Coyle et.al PVMRW 2010
Interconnect degradation Failure modes/mechanisms

Enhanced recombination–due to defect density in
1) bulk or
2) at grain boundaries of CIGS
& Shift in the Fermi level CIGS/CdS interface

- J-V parameters
  - $V_{oc}$, FF

- CC of ZnO:Al decreases
  - Affects FF (high ohmic losses in Front contact)

- Sheet resistance
  - Mo-P3 scribe
  - Performance loss

- Resistance
  - P2 contact resistance (Mo and ZnO:Al)

- CIGS absorber

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**Parameter** | **As-grown** | **500 h** | **1000 h**
--- | --- | --- | ---
Open circuit voltage (mV) | ~640 | ~540 | ~510
Fill factor (%) | 75 | 62 | 58
ZnO:Al front contact sheet resistance ($\Omega/\square$) | 10 | 20 | 30
Mo back contact sheet resistance ($\Omega/\square$) | 0.5 | 0.7 | 1
CIGS absorber resistivity ($\Omega$cm) | 20 | 10 | 10
P$_2$ contact resistance ($\Omega$cm$^2$) | $\sim 10^{-4}$ | $\sim 10^{-3}$ | $\sim 10^{-3}$
Mo sheet resistance in P$_3$ ($\Omega/\square$) | 0.5 | 100 | $\infty$

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“Deformation of the top bend is primarily driven by large expansion and contraction of the potting compound coupled with volumetric constraint offered by junction-box enclosure.”
Opportunities moving forward in CIGS reliability

• Standards
  – Develop standards (light soak, Indoor tests- Find acceleration factors)
  – Develop standard test structures for analyzing different failure mechanisms

• Indoor ALT’s - Identify Failure modes and mechanisms
  – Junction degradation (Relate Cell- Module reliability)
  – Interconnect (monolithic/cell based)
  – Packaging (Edge seal, EVA- Moisture ingress, PID)
  – Develop accelerated model

• Modeling
  – Thermal cycling, Mechanical failures

• Outdoor field performance:
  – Systematic metrology to understand field failures
  – Outdoor test individual modules and string outdoors in different climates and compare with field data

• Relate Indoor testing – Outdoor testing- bridge the gap.

• Develop a web based reliability-bankability comprehensive database
Acknowledgment

- U.S. DOE’s Sun shot Initiative
- College of Nanoscale Science and Engineering (Albany)
- Photovoltaic Manufacturing consortium
  - Solar Energy development center (at Halfmoon NY)

THANK YOU FOR YOUR ATTENTION!