CIGS Cell-Level Reliability Task and Studies at NREL

National Renewable Energy Laboratory

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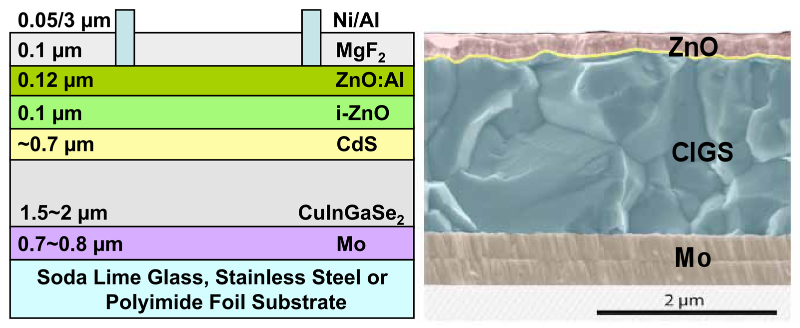
Task Objectives

Long-Term: To achieve high long-term performance reliability for thin-film CIGS PV modules with more stable materials, device structure designs, and moisture-resistant encapsulation materials and schemes.

Short-/Near-Term:
- To establish systematic experimental procedures and test designs,
- To identify degradation mechanisms & quantify degradation rates,
- To seek chemical / physical mitigation methods,
- To identify stable new materials or device designs,
- To develop/evaluate new encapsulation materials and schemes, especially for flexible CIGS.

Typical CIGS Device Structure



Performance Reliability Issues:
- Moisture Sensitivity of All Component Materials
- Glass/Glass Encapsulation with Desiccant Edge Sealant
- Damp Heat-Resistant, Light-Weight, Flexible Packaging

Main Subjects & Direction

Component-Level Materials and Reliability
- Mo, CIGS, ZnO, Alternative TCOs (Al:$Zn_{1-x}Mg_xO$, ITO, InZnO)
- Primary test conditions: Damp Heat (85°C, 85%RH, IEC61215, IEC61646), Dry Heat (<10%RH), and in Weatherometer (WOM).

Device Level Reliability
- Bare and Encapsulated CIGS solar cells

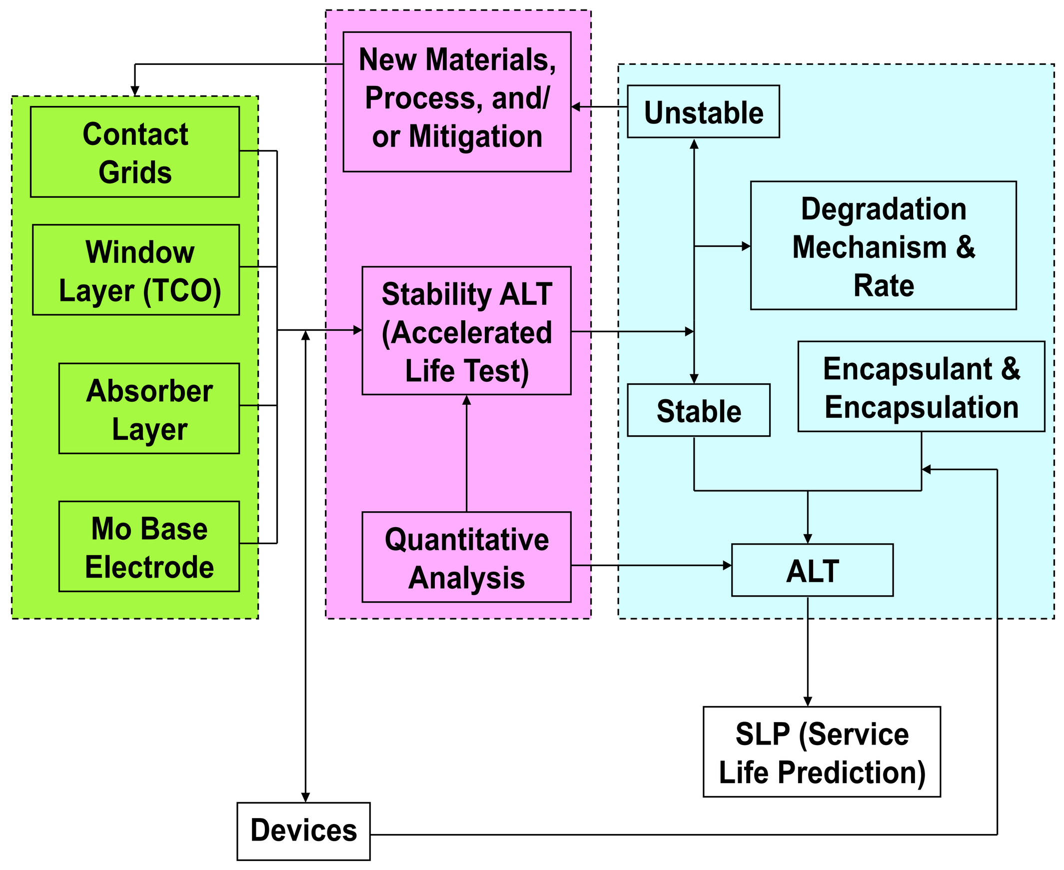
Chemical and Physical Mitigations
- Chemical formulations & application methods
- Moisture barrier oxides

Interconnect Technologies and Reliability
- Conductive adhesives for flexible interleafing connects
- All-Laser Scribing for P1, P2, and P3

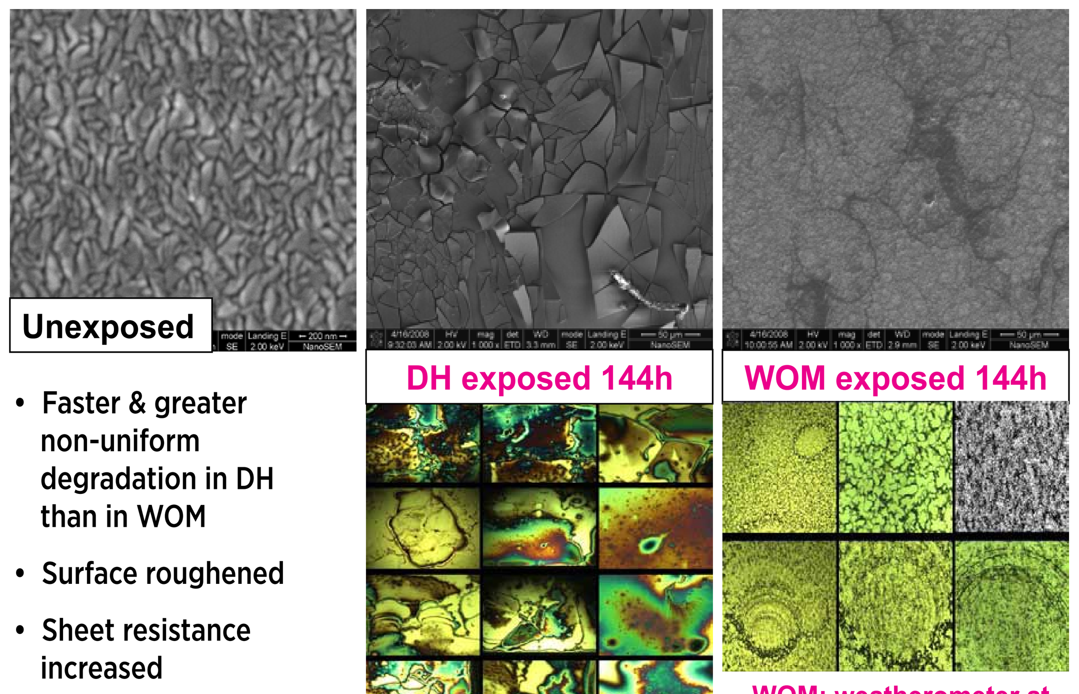
Development of Quantitative Analysis
- Non-invasive, non-destructive moisture ingress sensors
- Degradation rate vs. Moisture ingress rate/quantity
- New analytical method(s) and/or test structure design(s) for in-situ, on-device measurements.

Industrial Collaborations

Work Flowchart



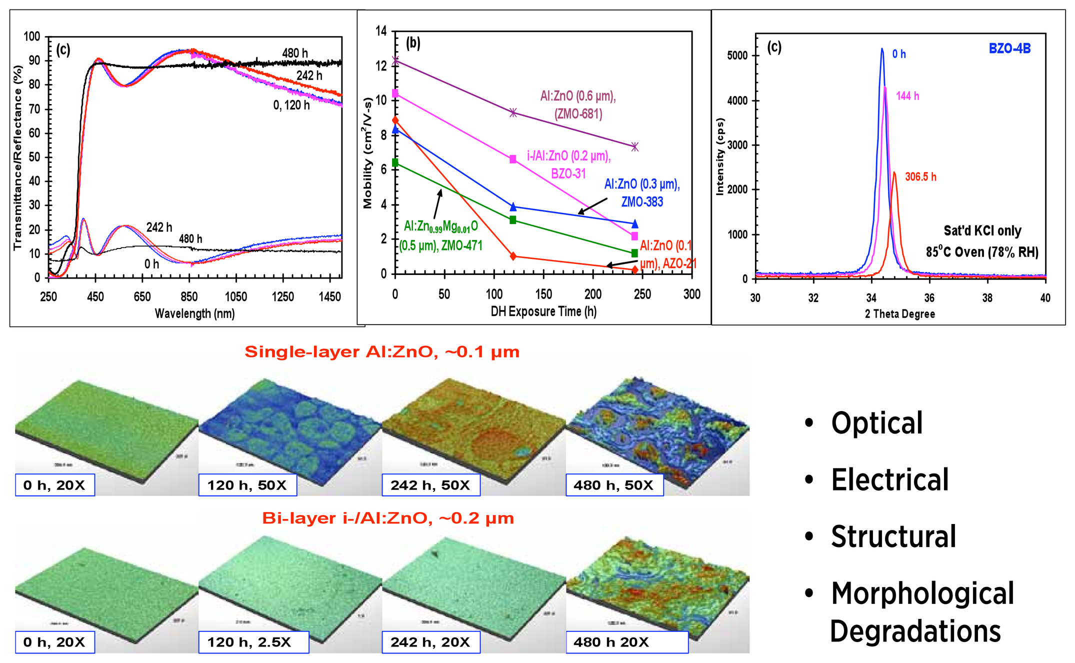
CIGS Component Reliability – 1
Degradation of Mo on SLG



- Faster & greater non-uniform degradation in DH than in WOM
- Surface roughened
- Sheet resistance increased
- Flaking/Delamination «

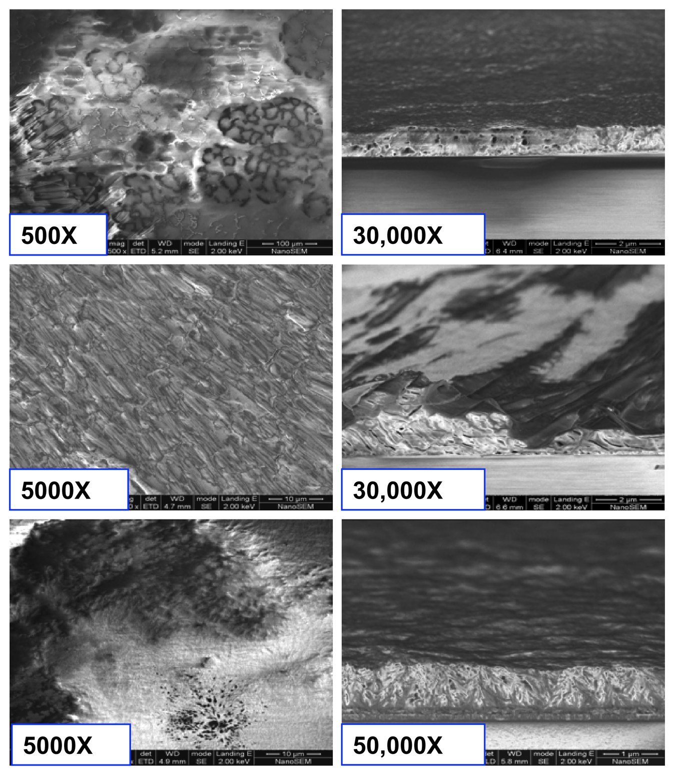
WOM: weatherometer at 2.5 UV-suns, 60°C, 60% RH

CIGS Component Reliability – 2a
Degradation of ZnO in DH



- Optical
- Electrical
- Structural
- Morphological Degradations

DH=480h ZnO Films Became Porous & 10-20X Thicker

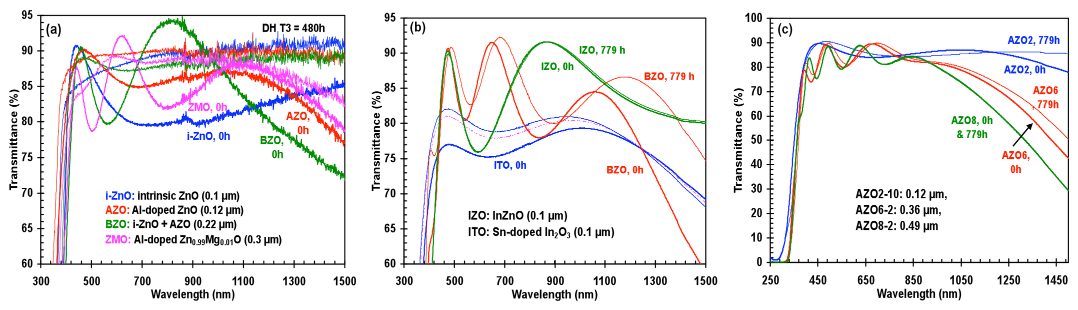


Al:ZnO (AZO) 0.12 µm => ~1.5 µm, porous, ring-like features

i-ZnO 0.1 µm => ~2 µm, porous, segregated (ditched)

i-/Al:ZnO (BZO) 0.22 µm => ~2 µm, porous, two layers

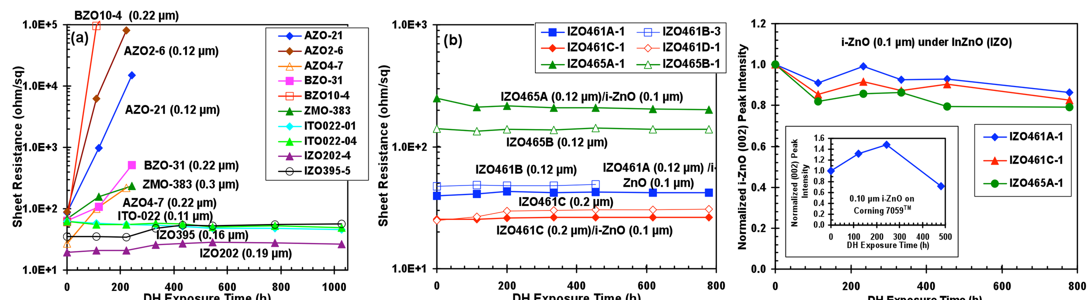
CIGS Component Reliability – 2b
Degradation of TCOs in DH



ZnO Films:
- Increased Transmittance due to Loss of Free Carrier Absorption
- Formation of $Zn(OH)_2$ and insulating ZnO (cubic)
- Thicker ZnO:Al (AZO) > Thinner AZO

DH Stability of TCOs: SnO:F > In_2O_3:Sn (ITO) ~ InZnO >> ZnO ~ ZnMgO

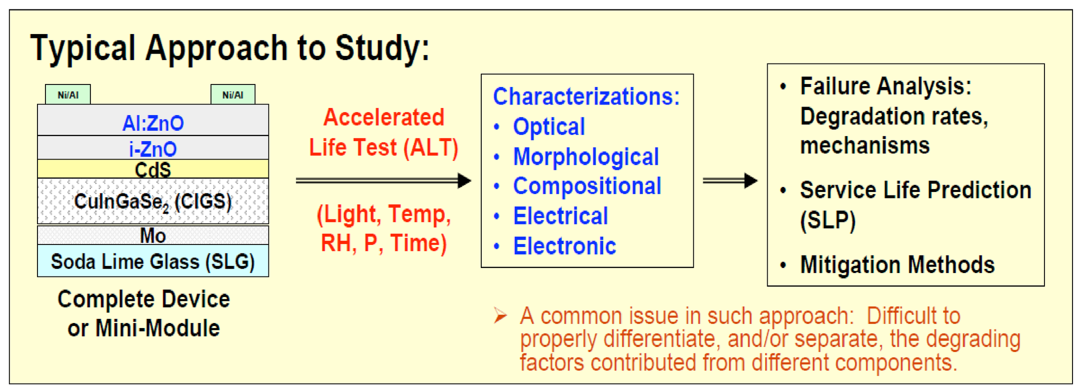
CIGS Component Reliability – 2c
Degradation of TCOs in DH

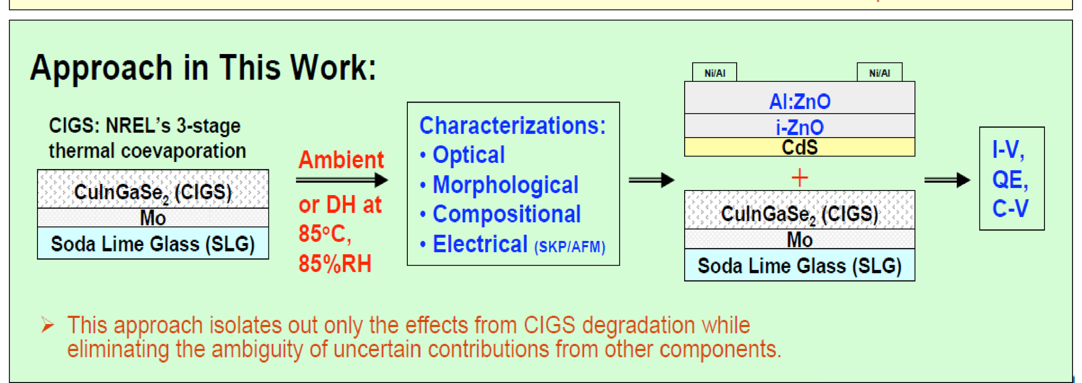


DH-induced Electrical Degradation:
- In_2O_3:Sn (ITO) < InZnO (IZO) << ZnO ~ ZnMgO
- Observed Variation in AZO and BZO degradation rates

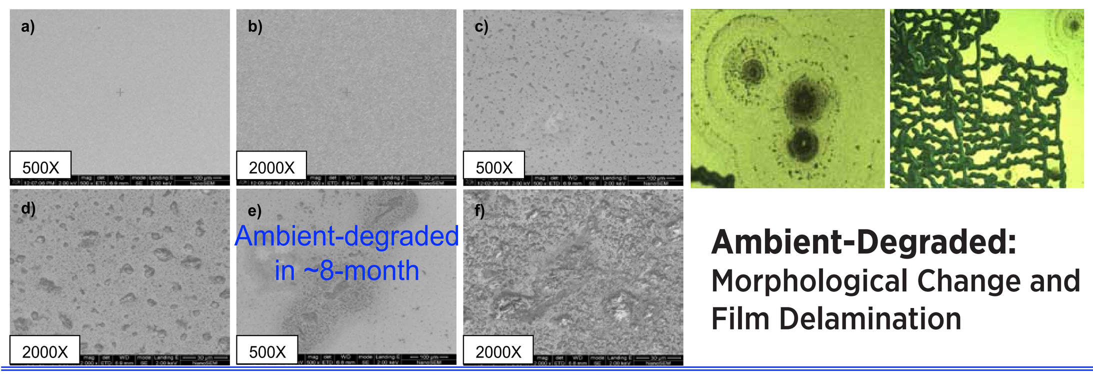
InZnO (IZO) offers protection of i-ZnO underneath.

CIGS Component Reliability – 3a
Humidity Susceptibility of CIGS Absorber

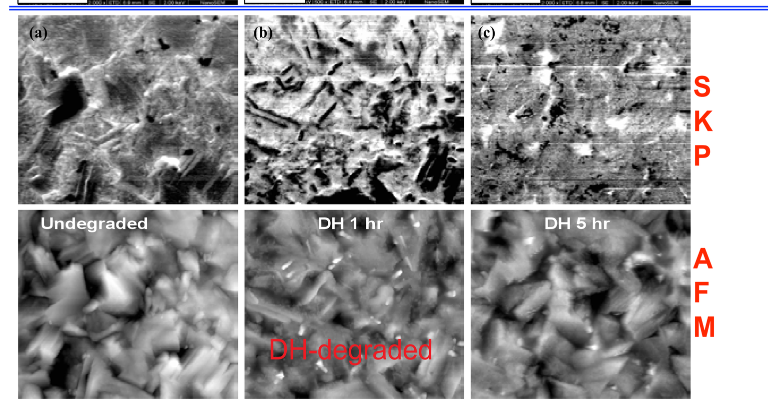




Humidity Susceptibility of CIGS Absorber



Ambient-Degraded: Morphological Change and Film Delamination



DH-Degraded: Work Function (Surface Potential) Change – Scanning Kelvin Probe (SKP) & AFM Analysis

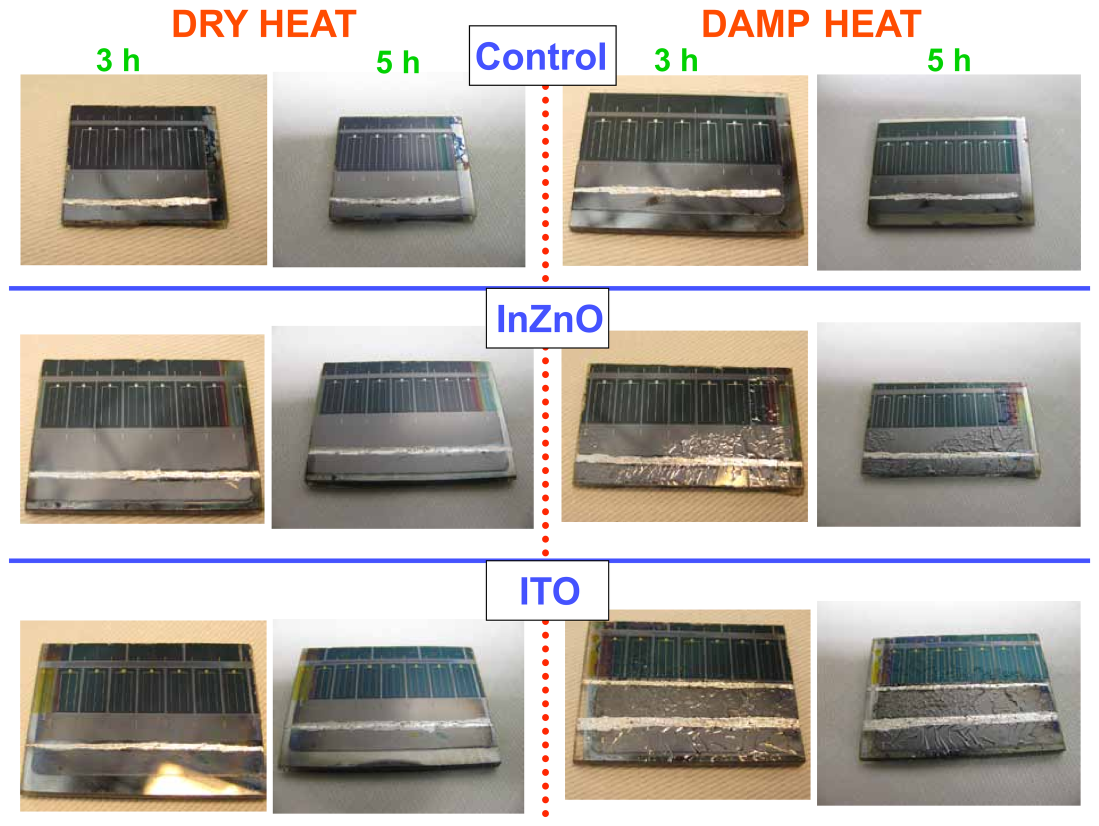
Performance of Devices made with Moisture-Degraded CIGS Absorbers

Table 2. Cell Parameters for CIGS Samples with or without Exposure to Ambient or Damp Heat

Sample ID	Exposure	Device No.	Voc (V)	Jsc (mA/cm^2)	FF (%)	Eff (%)	Rs (ohm-cm)	Rsh (ohm-cm)
A	ambient	1	0.415	10.30	34.3	1.5	16.8	58
		3	0.436	6.44	31.6	0.9	33.3	78
B	ambient	1	0.411	22.89	40.5	3.8	6.9	44
		4	0.385	25.67	44.9	4.4	4.5	55
C-1A	DH 15 min	2	0.544	30.84	65.6	11.0	2.5	413
		4	0.560	32.04	66.0	11.8	2.4	628
C-1B	DH 30 min	1	0.512	30.20	64.4	10.0	2.8	504
		3	0.513	30.91	63.7	10.1	2.8	376
C-0A	No (N2 dry box)	1	0.654	30.28	71.1	14.1	1.7	4491
		7	0.652	31.39	76.9	15.7	1.4	14126
C-0B	No (N2 dry box)	1	0.668	29.78	71.2	14.1	2.1	4228
		5	0.672	31.10	77.2	16.1	1.4	20536

- Prolonged ambient exposure resulted in very poor devices due to substantial compositional and morphological degradations on the absorber films. The devices' high series resistance (Rs) and low shunting resistance (Rsh) suggest that shorting and shunting had occurred.
- Brief exposures in DH for 15 min and 30 min readily induced significant efficiency losses.

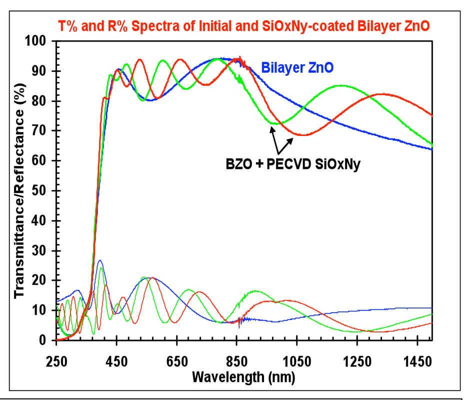
DH-Induced Delamination of Bare CIGS Devices

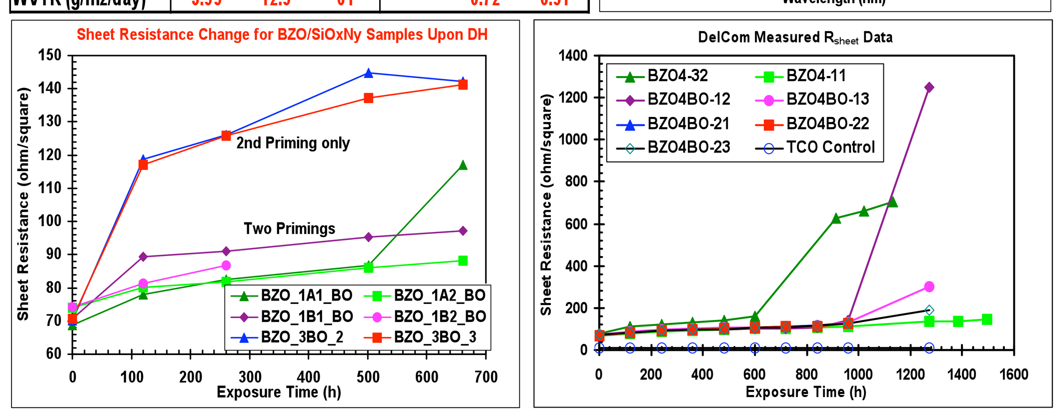


Chemical/Physical Mitigation for BZO

SiO_xN_y Barrier Oxide: blocks moisture effectively, shows optical effect by thickness, with better adhesion and DH resistance when coupled with chemical treatments

	Waver Vapor Transmission Rate (WVTR)					
Sample Film	Bare ST504 PET			SiOxNy Coated PET		
Temp (°C)	40	60	85	40	60	85
Breakthrough Time	40 min	10 min	2 min	n/a	1.5 hr	<15 min
WVTR (g/m2/day)	3.55	12.5	61		0.72	6.51

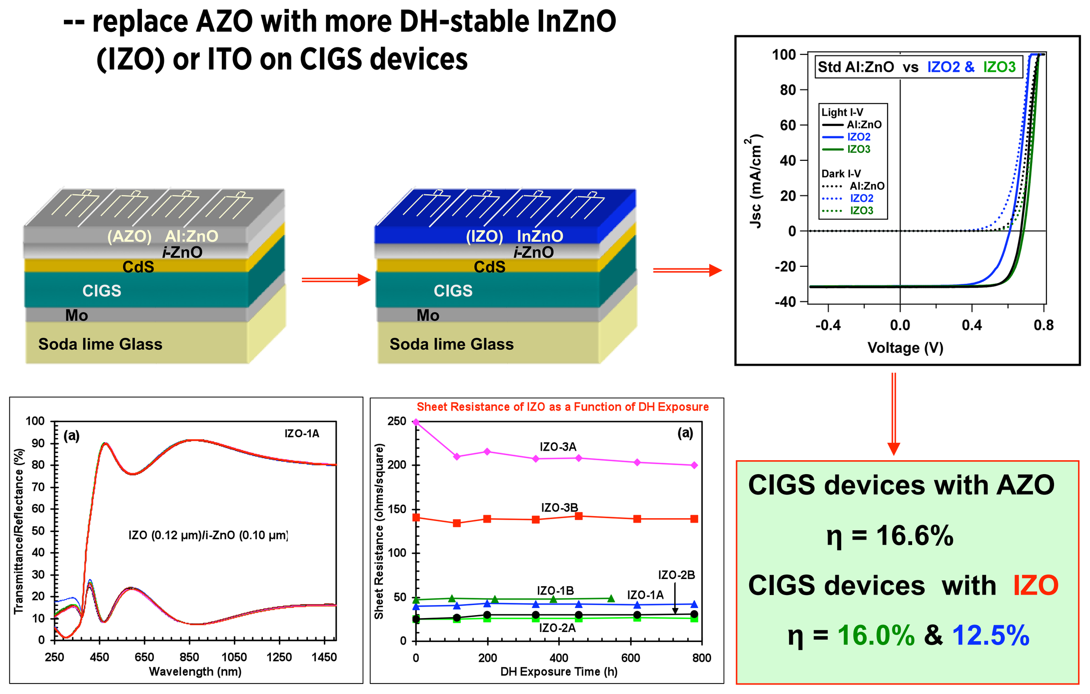




Mitigate DH-Degradation of CIGS Devices – Approach 2

Alternative TCO window layer

-- replace AZO with more DH-stable InZnO (IZO) or ITO on CIGS devices



CIGS devices with AZO

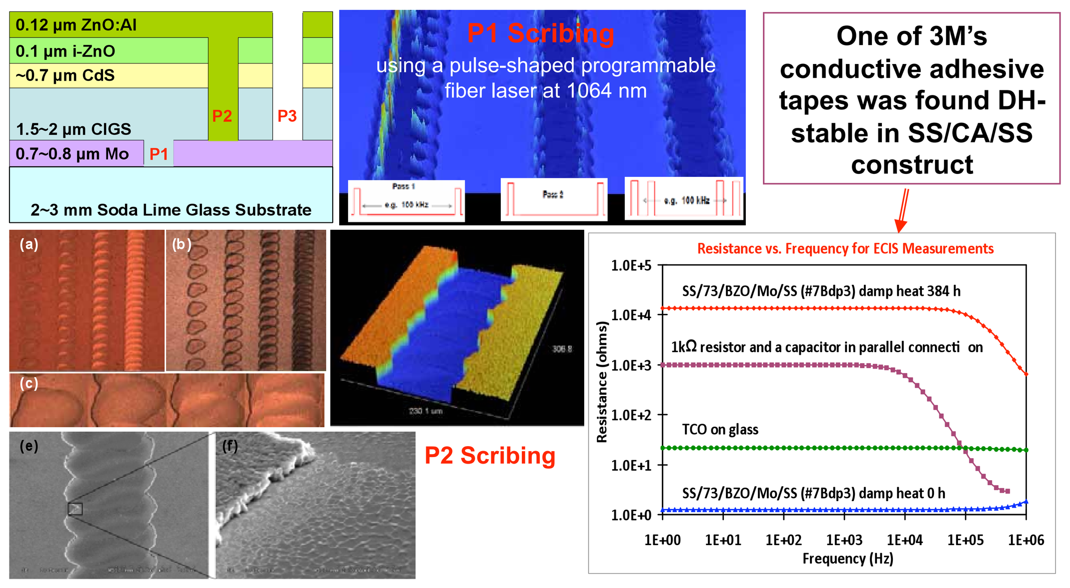
η = 16.6%

CIGS devices with IZO

η = 16.0% & 12.5%

Interconnects and Reliability

1. Developing "all laser-scribing" capability in collaboration with PyroPhotonics.
   - To Investigate performance and reliability of scribe lines and mini-modules
2. Investigated the DH stability of *"shingling" (interleafing)* interconnection using conductive tape on stainless steel substrates



One of 3M's conductive adhesive tapes was found DH-stable in SS/CA/SS construct

Industrial Collaborations / Task Publications 2009

- Thin-Film CIGS Glass/Glass Mini-Module and Edge Sealing: (JLN Solar, WFO)
- Conductive adhesives for interleafing connects: (3M)
- Laser Scribing: (PyroPhotonics)
- CIGS Encapsulation and Reliability Testing: (Optony)
- Flexible CIGS Packaging: (Sandia Solar)

1. "Module Encapsulation Materials, Processing, and Testing," John Pern, APP International PV Reliability Workshop (IPRW-I), Dec. 4-5, 2008, SJTU, Shanghai, China.
2. "Stability Issues of Transparent Conducting Oxides for Thin-Film Photovoltaics," John Pern, APP International PV Reliability Workshop (IPRW-I), Dec. 4-5, 2008, SJTU, Shanghai, China.
3. "Investigation of the Stability Issues of TCO Barrier Layers for CIGS Devices upon Damp Heat and Dry Heat Exposures," Raji Sundaramoorthy, Ingrid Repins, David Albin, Tom Gennett, Jian Li, John Pern, and Tim Gessert, APS, March, 2009.
4. "Preliminary Evaluation of Conductive Adhesive Tapes as Potential Interleafing Connects for Flexible Thin-Film PV Applications," F. J. Pern, R. A. Jones, L. M. Gedvilas, and T. A. Gessert, MRS Spring, San Francisco, CA, April 2009.
5. "A Study on the Humidity Susceptibility of Thin-Film CIGS Absorber," F. J. Pern, B. Egaas, B. To, C.-S. Jiang, Jian V. Li, S. Glynn, and C. DeHart, 34th IEEE PVSC, 6/7-12/2009, Philadelphia, PA.
6. "Comparison of Amorphous InZnO and Polycrystalline ZnO:Al as A Conductive Layer for CIGS PV Solar Cells," R. Sundaramoorthy, I. L. Repins, T. Gennett, Jian V. Li, D. Albin, F. J. Pern, C. DeHart, S. Glynn, J. Perkins, D. Ginley, and T. Gessert. 34th IEEE PVSC, 6/7-12/2009, Philadelphia, PA.
7. "Humidity-Resistant High-Conductivity Amorphous-InZnO Transparent Conductors," T. Gennett, D. T. Gillaspie, M. O. Reese, L. J. Simpson, F. J. Pern, J. D. Perkins, and David S. Ginley, 34th IEEE PVSC, 6/7-12/2009, Philadelphia, PA.
8. "Stability of TCO Window Layers for Thin-Film CIGS Solar Cells upon Damp Heat Exposures – Part II," R. Sundaramoorthy, F.J. Pern, C. DeHart, T. Gennett, F.Y. Meng, M. Contreras, and T. Gessert, SPIE PV Reliability, 8/2-6/2009, San Diego, CA.
9. "Stability of TCO Window Layers for Thin-Film CIGS Solar Cells upon Damp Heat Exposures – Part III," F. J. Pern, S. H. Glick, X. Li, C. DeHart, T. Gennett, M. Contreras, and T. Gessert, SPIE PV Reliability, 8/2-6/2009, San Diego, CA.