The challenges in understanding CIGS thin film cell and module reliability

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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

DOE | CNSE | SEMATECH

INDUSTRY

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PVMC

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

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PVMC Multi-Year Strategy: 3 year and beyond

	Yr1	Yr2	Yr3	Yr4	Yr5	Partners	Objectives/Tasks
(FEOL) PV Cell Manufacturing						Equipment/Material Metrology/Suppliers, R&D Companies	Manufacturing Productivity, Cost Model, Metrology
(BEOL) Module Manufacturing						Equipment/Suppliers, PV and Roofing Manufacturers	Effectiveness, Life cycle, Reliability, Metrology Testing, Quality,
Roof Integration						Architects, Installers, Roofers, Contractors, Utilities	Design, Standards, Testing, Installation, Reliability, BOS
LPV Deployment						Utilities, Installer, End Users , Building Owners	Commercialization, Field Test, System Cost, Grid Integration

Current PVMC Members, Research Partners and Supply Partners

SCHLUMPF USA
INFINITY Precision Systems
BROOKHAVEN NATIONAL LABORATORY
Magnolia Solar
Sandia National Laboratories
PROCESS RESEARCH PRODUCTS
SOLLIANCE SOLAR RESEARCH
Tau Science Process Control for PV
CERES TECHNOLOGIES
AST
SUNY College of Nanoscale Science and Engineering
zapp
INDIUM CORPORATION
OPTIMATION
Investment Grade MMRA Roofing
i2ds
University of Central Florida 1963
CONVERTECH, INC Delivered fast and built to last
MUSTANG SOLAR PRODUCTION EQUIPMENT
SCI Engineered Materials, Inc.
Sinton instruments
MiaSolé
coilpro MACHINERY Slitters • Oscillators • Edgers
Sonoscan Sound Technology With Vision
NREL NATIONAL RENEWABLE ENERGY LABORATORY
Veeco
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CS CLEAN SYSTEMS
ANP Advanced Nano Products
Newport Experience | Solutions
GLOBAL SOLAR
SEMATECH Accelerating the next technology revolution.
PerkinElmer For the Better
ITN ENERGY SYSTEMS INC.
ENrG Inc.
Celebrating Forty Years of Innovation spire
COLNATEC
Ultrasonic Technologies, Inc
ANP Advanced Nano Products
PLANSEE
EsgeeTechnologies Inc. Analysis and Design through High-Fidelity Simulations
MCA METAL CONSTRUCTION ASSOCIATION
INFICON
semi
VersulfleX Technologies
POLARITEK
5N PLUS
pearllaboratories
NIABRAZE
Direct solar
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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

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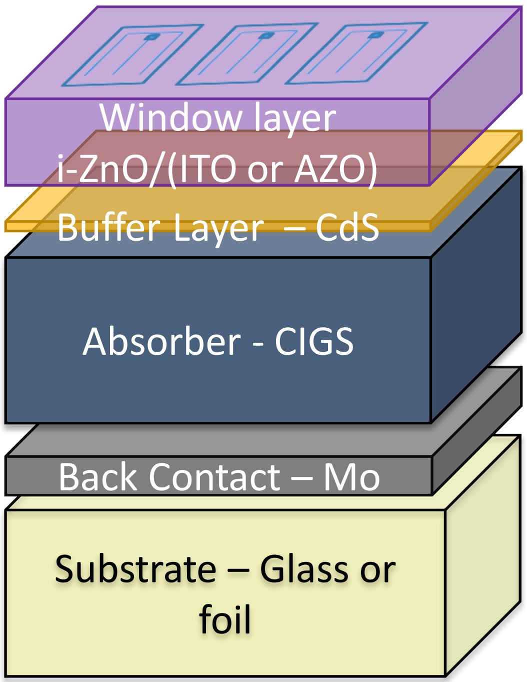
CIGS device stack - Deposition methods and materials



Co-evaporation example	Alternatives
Grids: Evaporation Ni (150-500A) Ag (5000-6000A) Al(2-3μ);	**Grids/ Screen print/wire overlay/ tab and string diff interconnects**
Window layer: Sputter Resistive: i-ZnO-0.1-.12μ; Conductive:AZO- 0.1-.15μ	**Window layer: MoCVD Zno:B; InZnO; ITO**
Buffer Layer: Chemical bath deposition (CBD) CdS, ~20-80nm;	**Buffer Layer: Chemical bath deposition (CBD)/Sputter: Zn(O,S); ~20-80nm;**
CIGS: 1stage/2 stage /3 stage Cu, In, Ga are co-evaporated in Se overpressure CIGS- ~1-2μ	**CIGS: Reactive sputtering, Ink deposition/ coating, Selenization, Co-evaporation**
Molybdenum-Sputter; ~0.3-1μ Barrier layers:Cr/Nitride	**Na barrier/ Se barrier/ Oxide barrier**
Glass:2mm or 3.2mm Stainless foil: ~25μ	**Aluminum Polyimide**

Deposition methods & Thickness

In-depth analysis using different characterization techniques is required to understand the interfacial properties-Include Na incorporation

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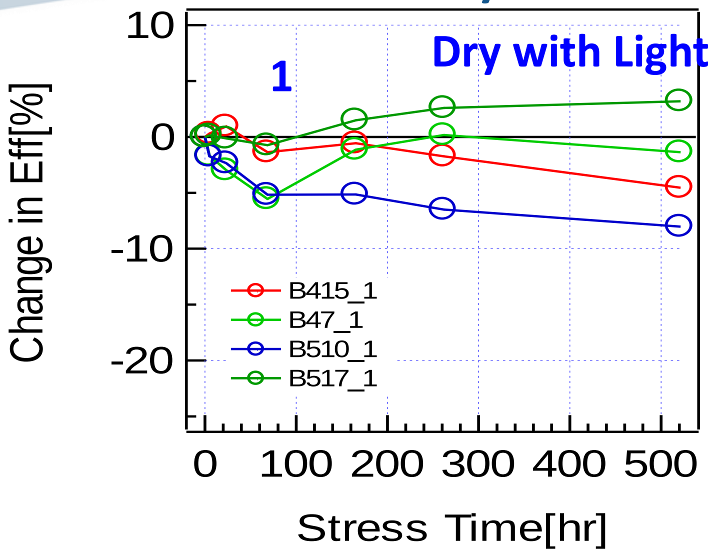
Device efficiency- Moisture and Temperature/Light Effects



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}**

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

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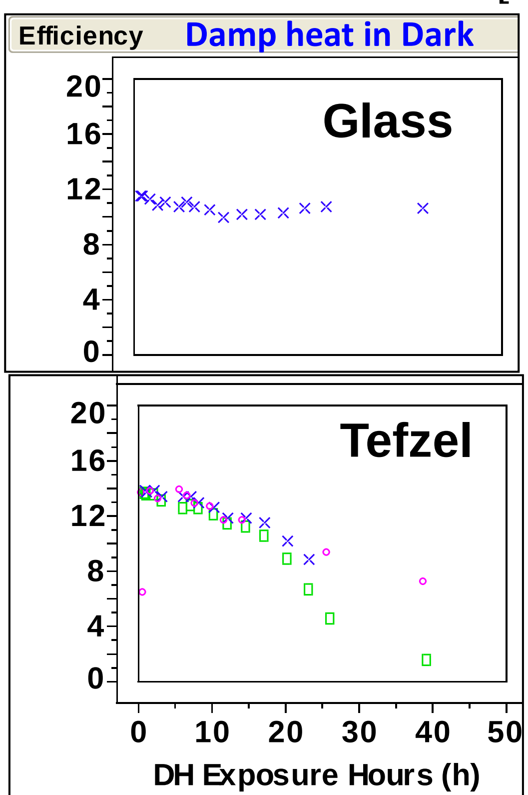
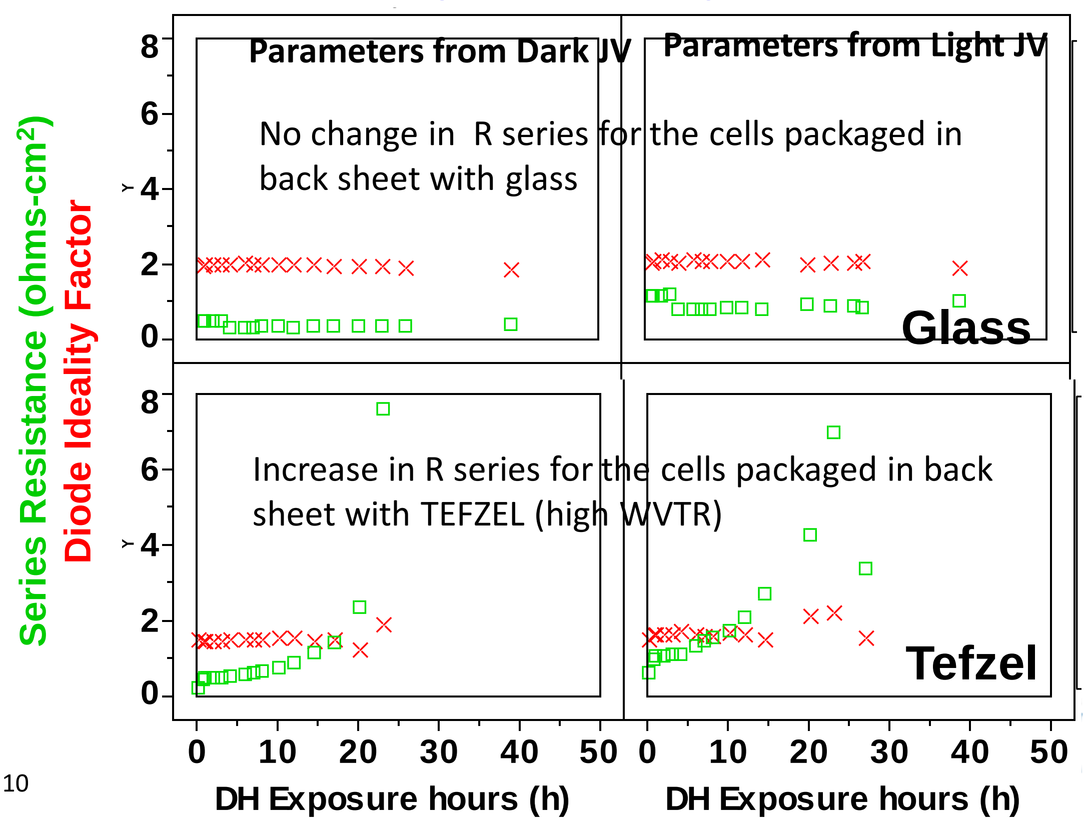
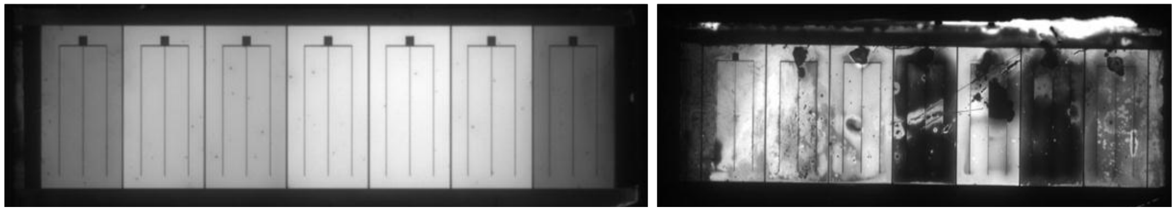


Modeling of Dark and light JV curves



Recombination and lifetime- correlation

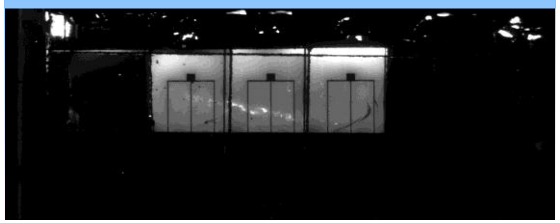
Before DH **After DH**



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.37[th] IEEE-PVSC

PL image after re-fabrication of the DH exposed device



TRPL measurements after DH exposure

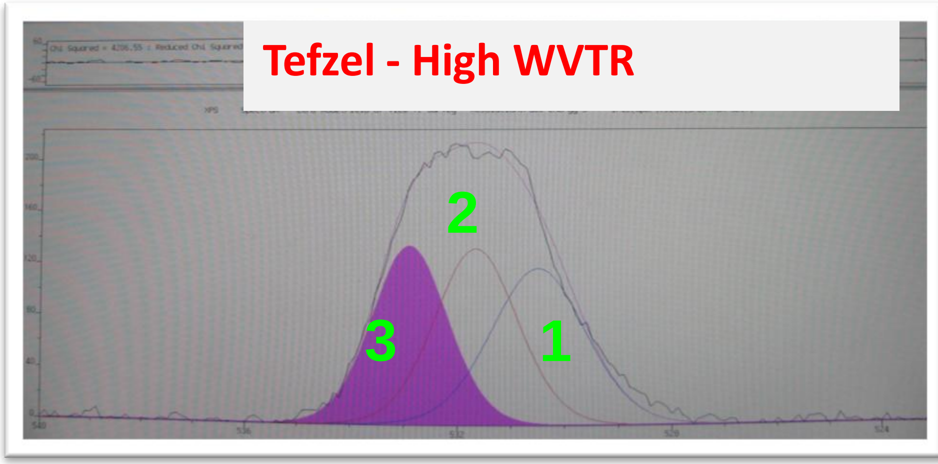
Back sheet	Lifetime τ_1 (ns)
N/A, stored in ambient	6.25
Glass	8
TPAT	8.56
TPT	8.87
Tefzel	1.85

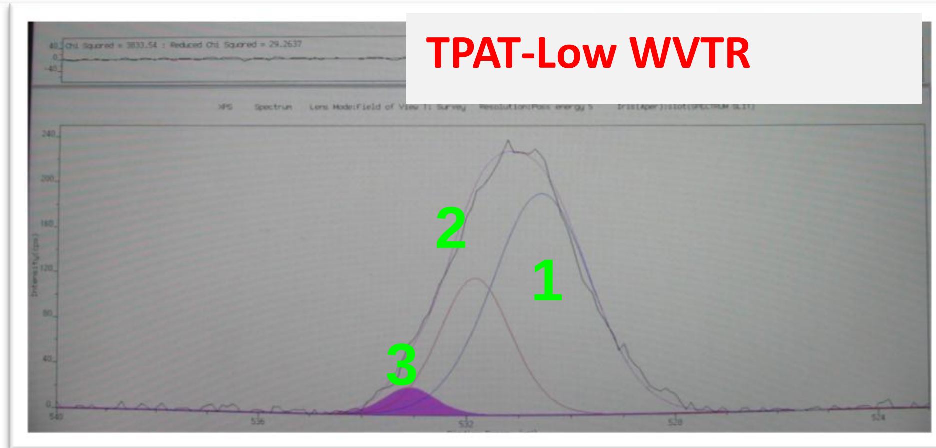
DH Exposure Time (h)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	Efficiency (%)
0	0.69	32.8	78	17.7
1	0.64	28.1	58	10.4
784	0.65	19.9	59	7.6
N/A, after refabrication	0.56	28.4	60.9	9.68

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



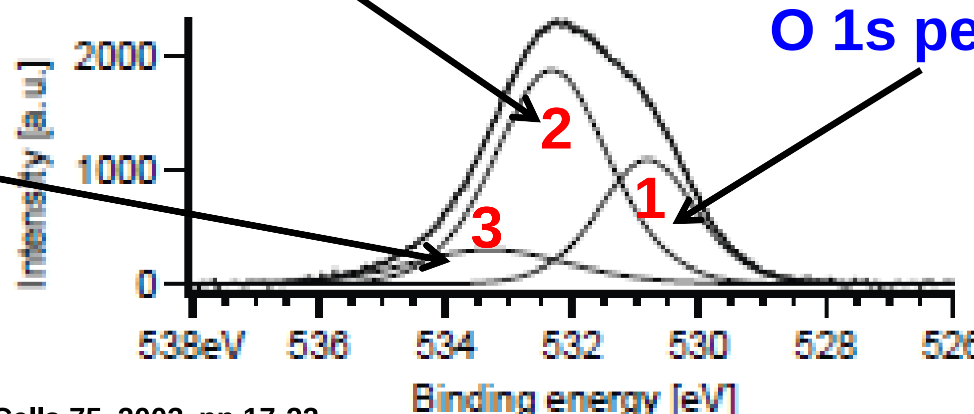


Evidence of hydrolysis of ZnO (TCO) and moisture in TCO Formation of $Zn(OH)_2$ after DH exposure and moisture trapped in the devices packaged with backsheet having high WVTR

(531.5–532.2 eV)
$Zn(OH)_2$

529.9–530.7 eV
O 1s peak

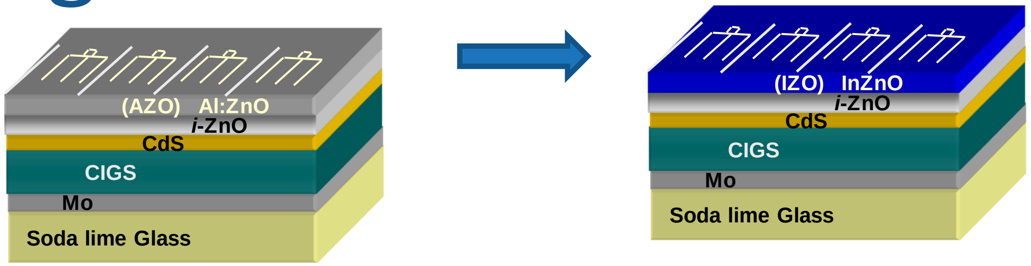
(532.8–534 eV)
adsorbed water



W. Eisele, et. al.*Solar Energy Materials and Solar* Cells 75, 2003, pp.17-23.

TCO Engineering- device level

One approach for CIGS devices for improving device performance in DH



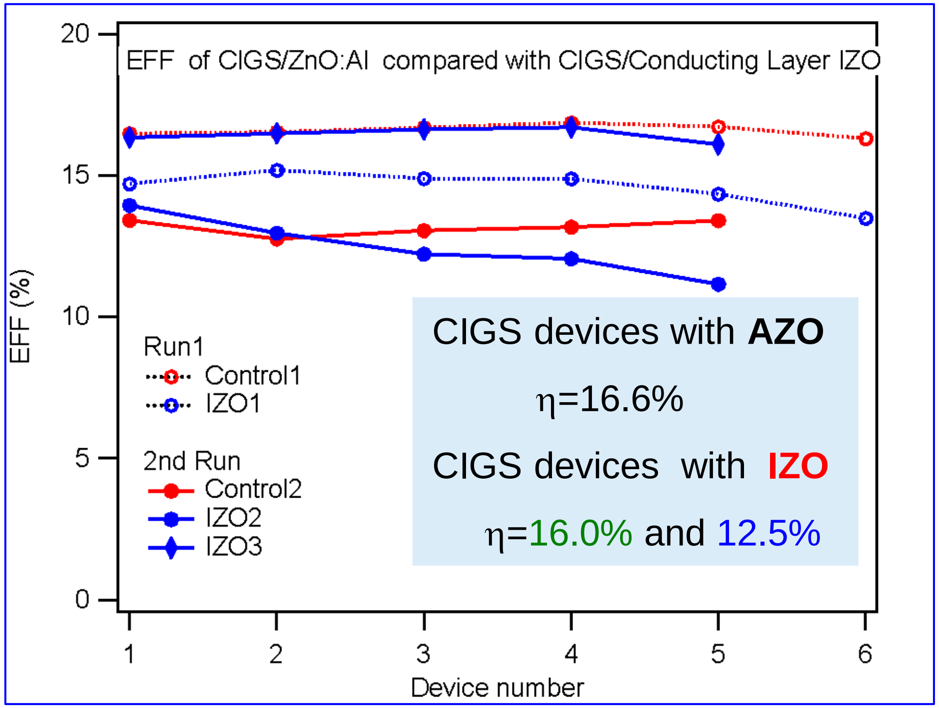
❖Alternative TCO which is DH stable

IZO (InZnO) for CIGS

- ➢Conductive layer (i-ZnO/c-InZnO)
- ➢Bi-layer(i-InZnO/c-InZnO)

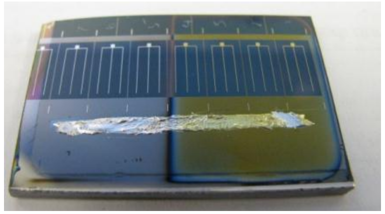
R. Sundaramoorthy et.al 34th IEEE-PVSC

Comparable efficiencies with alternative conducting TCO which is DH stable

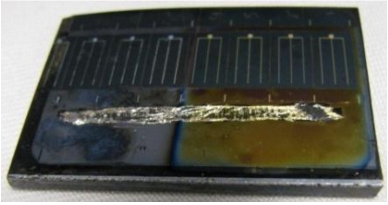


❖Barrier layers on CIGS (TCOs and PTMO)

Un exposed



After 38h in DH



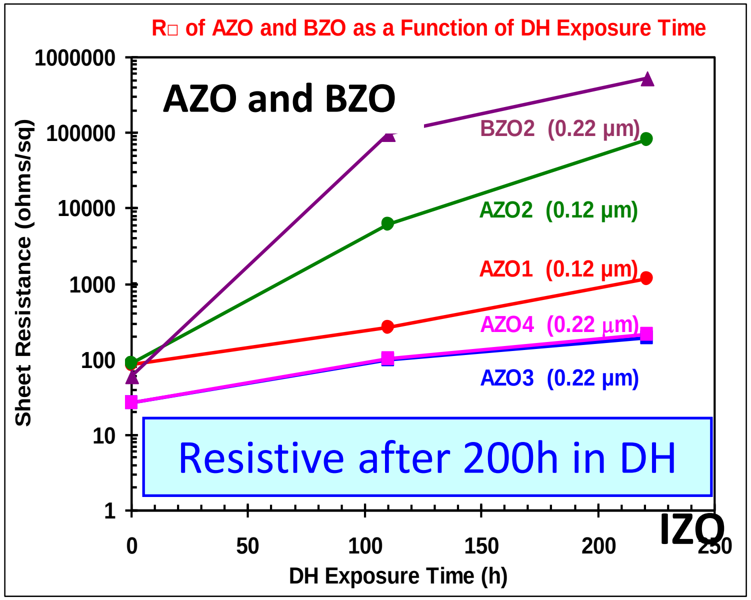
PL Image after DH exposure

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

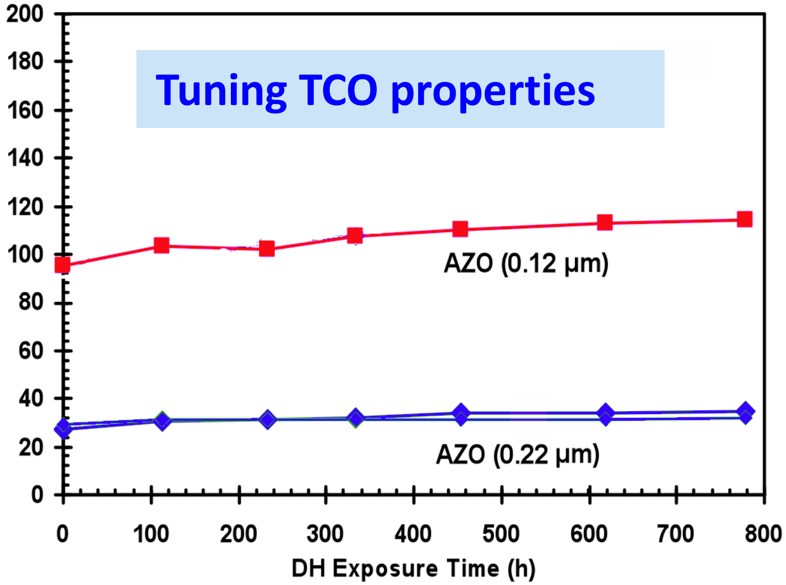
Unit film Engineering



Order of decreasing stability:

ITO ~ InZnO >>B:ZnO >>>Al:ZnO ~ BZO

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



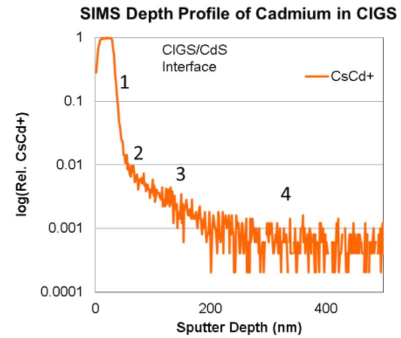
Important properties of TCO for DH stability

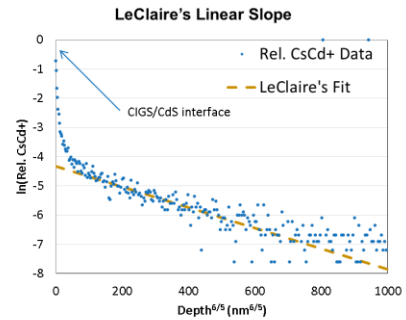
- Thickness of the film, Sheet Rho
- Grain boundaries
- Bias conditions, (Processing parameters)
- Multi-layers of same or different films has profound effect on the stability of the TCO

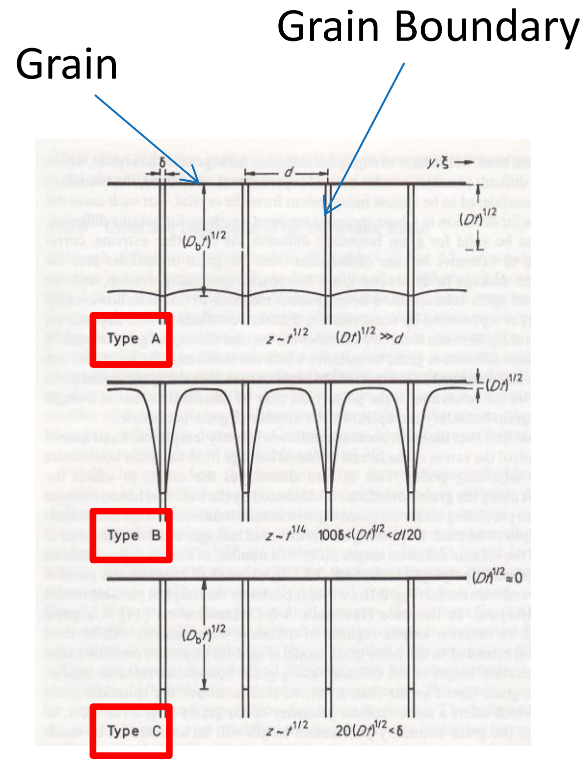
Understand Long term reliability- CdS diffusion in CIGS failure mechanisms

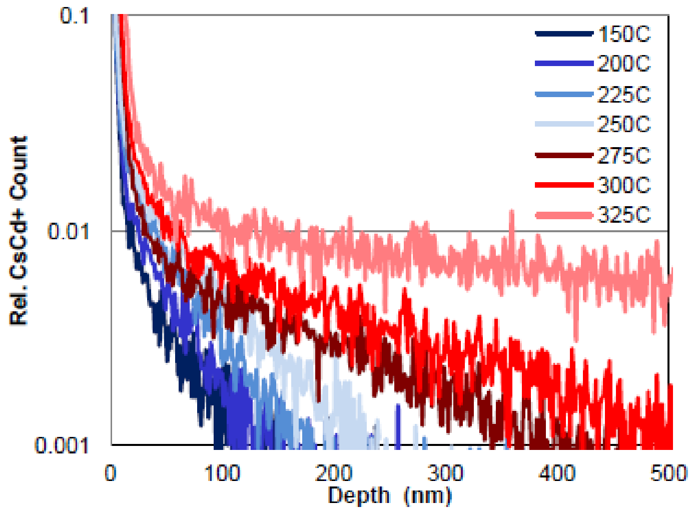
- Failure physics correlated to mass transport kinetics
  - Diffusion via lattice (volume)
  - Diffusion via grain boundary

- SIMS analysis –
  - affected by Surface roughness
- Polish CIGS /Deposit CdS









Region 1 – Volume diffusion from the surface
Region 2 – Volume and grain boundary diffusion
Region 3 – Grain boundary diffusion
Region 4 – Background noise level

LaClaire's analysis

$$s\delta D_b = 1.32(D/t)^{1/2}(\partial ln\bar{c}/\partial z^{6/5})^{-5/3}$$

$$\ln\left(\frac{D_b}{\sqrt{D}}\right) = \ln\left(\frac{D_{bo}}{\sqrt{D_0}}\right) + \frac{1}{T}\left(\frac{\frac{1}{2}\Delta E - \Delta E_b}{k}\right)$$

The activation energy for volume diffusion of cadmium in CIGS is ~1 eV [2]

Thus ΔE_b is ~0.7 eV ; Equation necessarily suggests $\Delta E_b > ½\Delta E$

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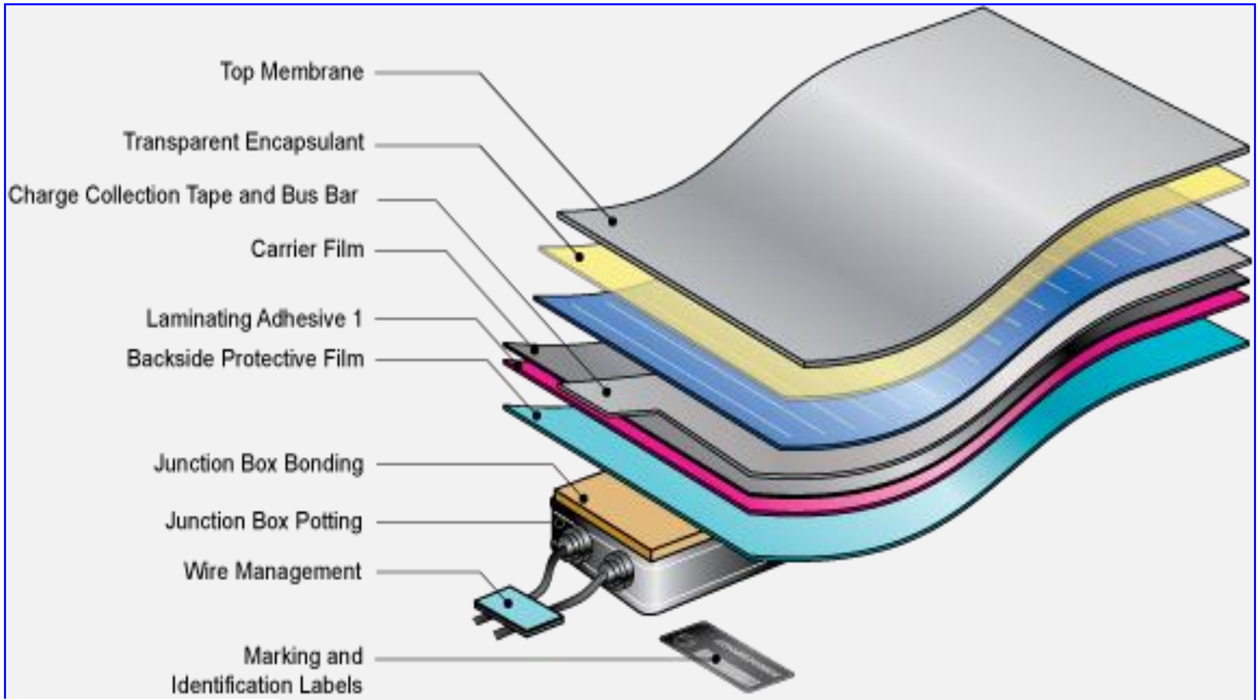
Module level reliability
Field failures
Indoor Accelerated Lifetime Tests (ALT’s)
Interconnect reliability
Modeling

CIGS Module (Rigid/Flexible)



Deposition method	Company
Co-evaporation	Wurth, GSE, Ascent, Solibro
Selnenization	Solar frontier, Avancis, STION , TSMC
Sputtering	Miasole
Nanoparticle	Nanosolar, ISET,-Pioneer products
Electroplating	Solopower/NEXCIS
FASST and other process	Heliovolt

Different ways of fabricating CIGS

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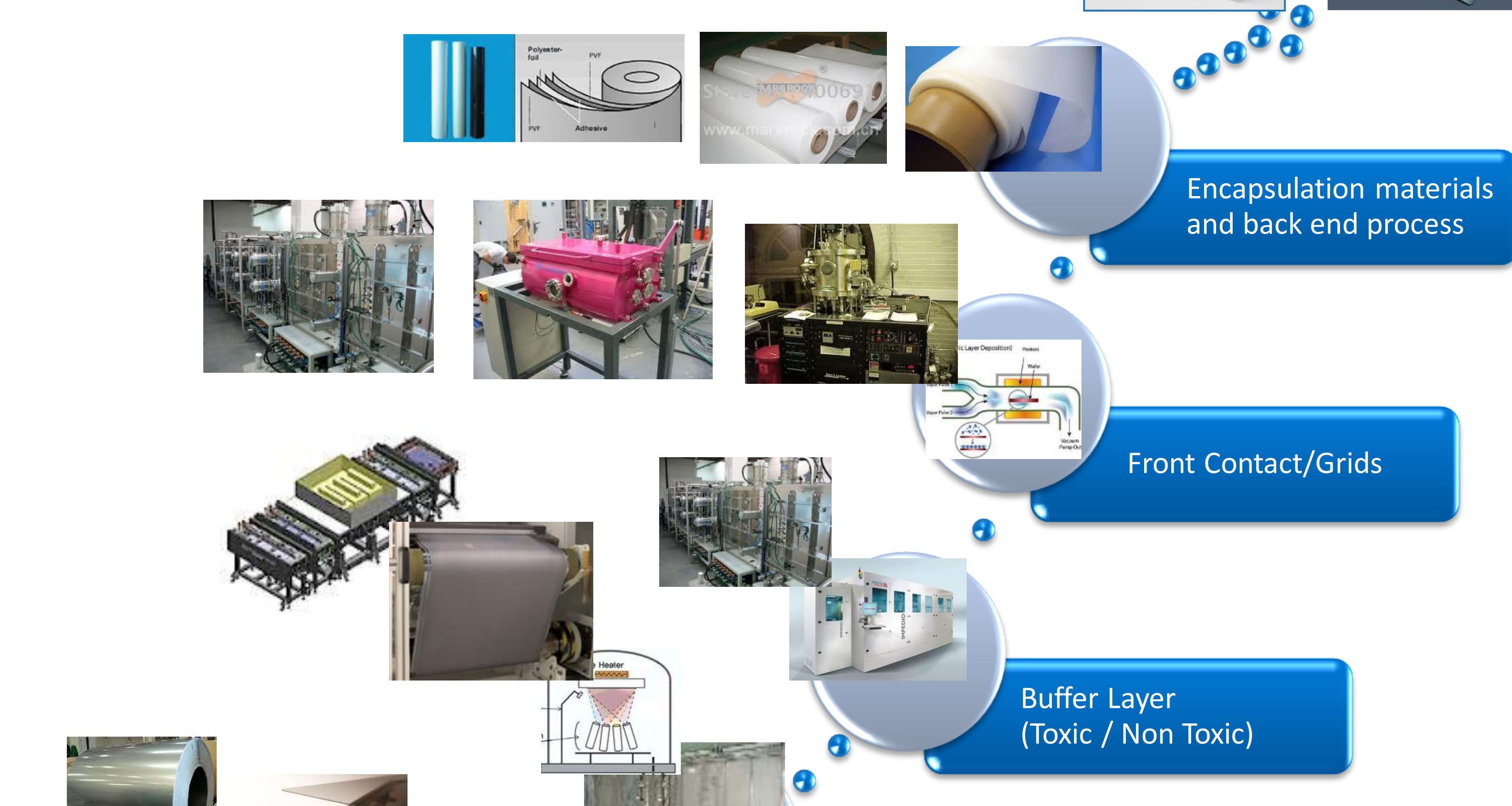
Module manufacturing



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.

History of Qualification Tests –Certification Standards

c-Si | PVB encapsulants- with glass Corrosion of metallization | IEC 61215 | EVA

Test	I 1975	II 1976	III 1977	IV 1978	V 1979
Thermal Cycles	100 -40 to +90	50 -40 to +90	50 -40 to +90	50 -40 to +90	200 -40 to + 90
Humidity	70C,90% 68 hrs	5 cycles 40 to 23C 90%	5 cycles 40 to 23C 90%	5 cycles 54 to 23C 90%	10 cycles 85 to -40C 85%
HOT SPOT					3 cells 100 hrs
Mechanical Load		100 cycles 2400 Pa	100 cycles 2400 Pa	10000 2400 Pa	10000 2400 Pa
Hail				9 impacts ¾" –45 mph	10 impacts 1" – 52 mph
High Pot		<15 µA 1500 V	< 50 µA 1500 V	< 50 µA 1500 V	< 50 µA 2*Vs+1000

Silicone encapsulant - no glass

Modules in deserts

IQT ↔ IEC61215

IEEE 1262

Thin film product IEC 61646

Qual test for Thin film PV modules built around c-Si PV failure modes.

PVMRW2010- John Wohlgemuth

Qualification testing is confused with reliability testing

Incorporates pass/fail criteria- **DOES NOT PREDIT 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.

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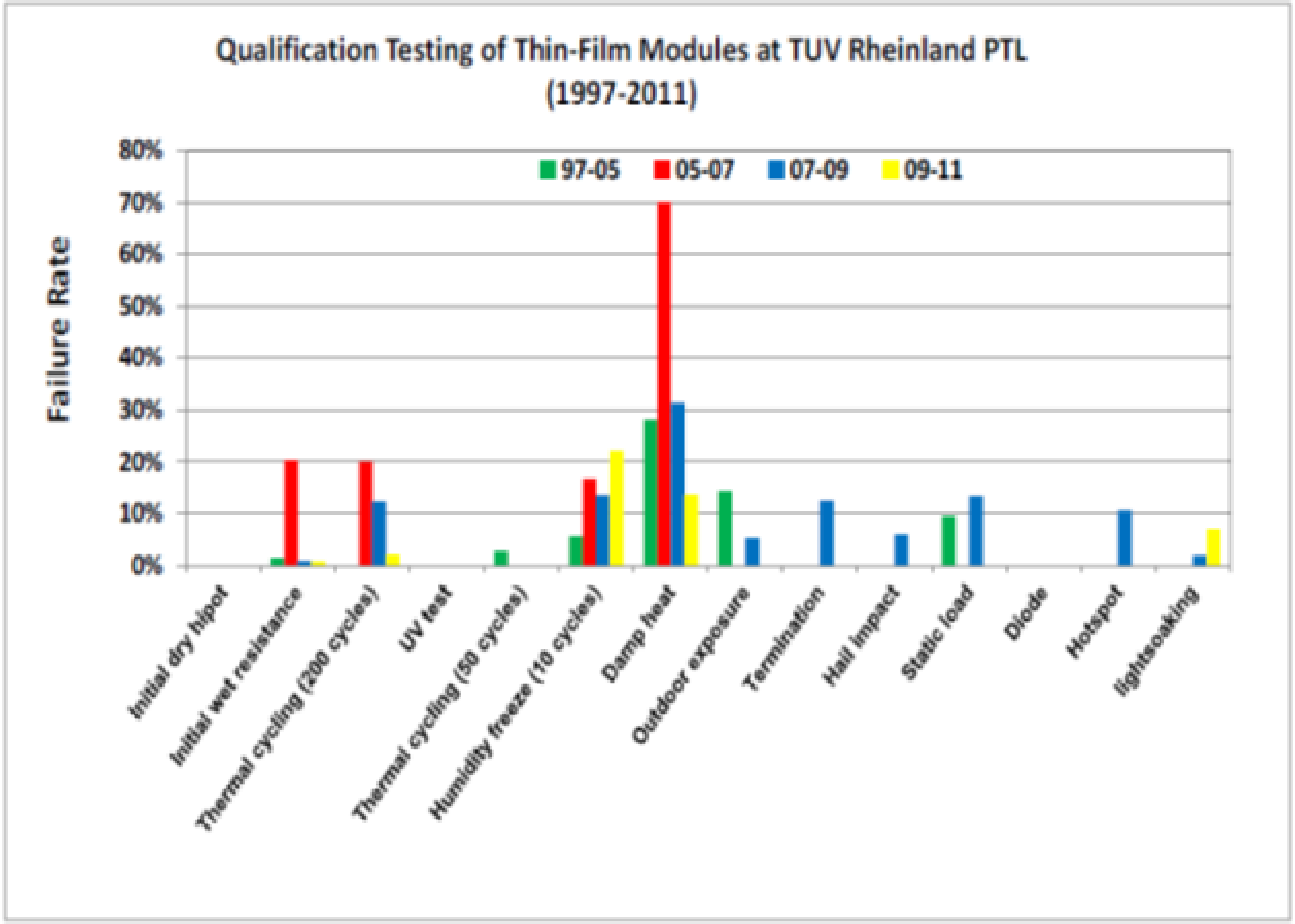
Where does the failure occur in TF-PV?



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?

TUV 1997-2011 Failure Rate Analysis of Module Design Qualification Testing - IV: 1997-2005 vs. 2005-2007 vs. 2007-2009 vs. 2009-2011; G. TamizhMani, et.al. TUV Rheinland PTL

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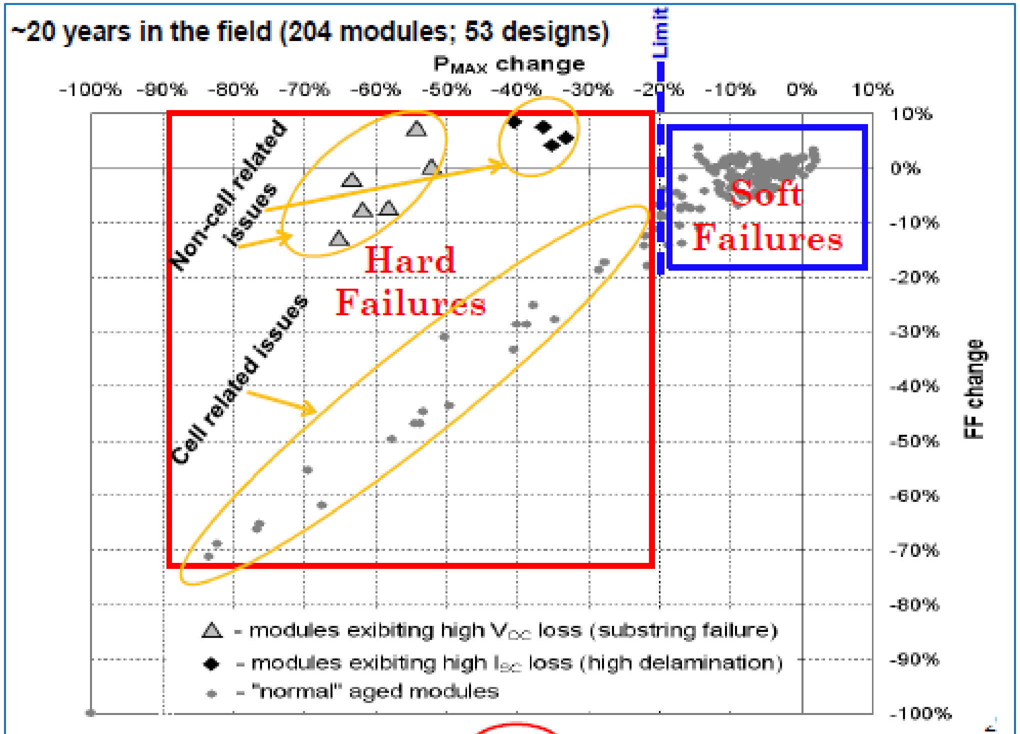
Design differences



18-24 Years Modules, Ispra, Italy (Source: ESTI)

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

(Data from field : 203 modules and 53 designs)

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!

Design differences in current CIGS module manufacturing approach

Tab and string

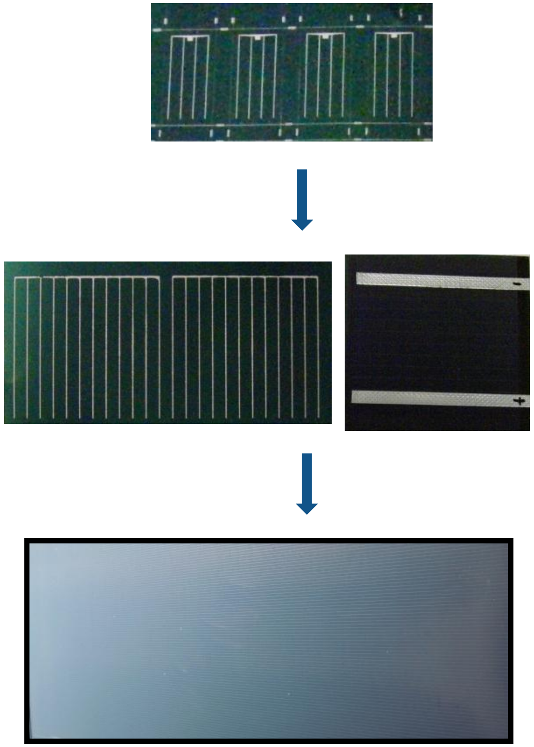
Wire method

CNSE : Roof top Array

Monolithically integrated

Indoor Accelerated Lifetime Tests

- Junction degradation
- Packaging
- Interconnect degradation
- Barrier layers



Need to establish

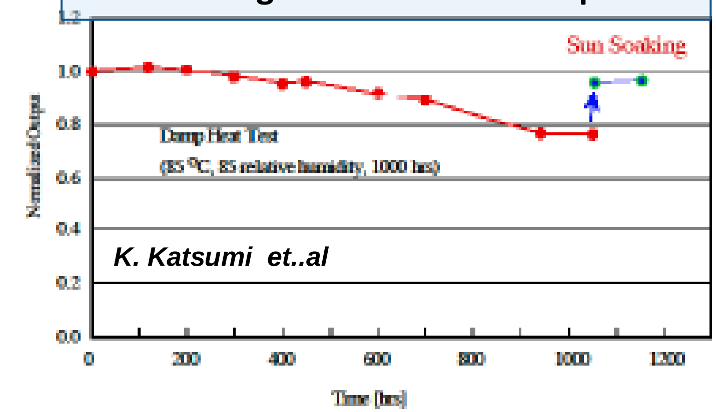
- Standard structure for a failure mechanism.
- ALT's beyond normal acceleration-combinatorial tets
  - Chamber options((DH/Dry)- with Light/ HALT/ HASS)
- Protocols for measurements (Combinatorial/Stress order/ Load/In-situ/ **N**ormal **O**perating **C**ell **T**emperature (NOCT)/**S**tandard **T**esting **C**onditions (STC)
- Protocols for combinatorial stress factors (RH, T, Bias, Mechanical) + Pre conditioning)

Effect of light, temperature and moisture

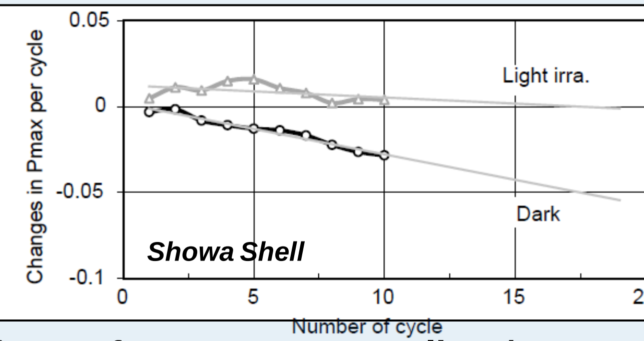
<u>Indoor:</u> Light Soak after DH exposure for 1000hrs
<u>Outdoor</u> : Enhancement in efficiency by outdoor light soaking for 3-4 hrs after fabrication

<u>Probable reason:</u> 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

Effects of Light soak after DH exposure



Effects of light on modules in DH chamber



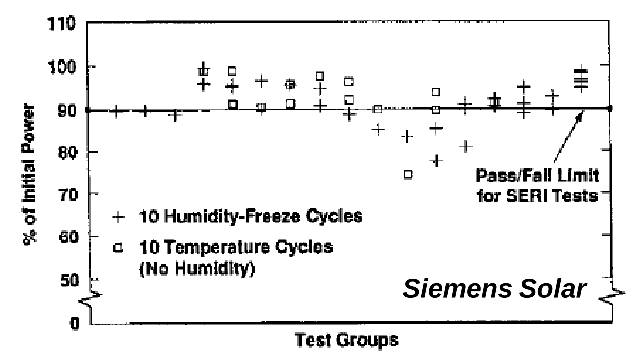
Effects of Temperature cycling / HF cycles

<u>Indoor</u> : DH exposure with and without light exposure

Degradation in the presence of light

is less than

degradation in Dark -Damp heat

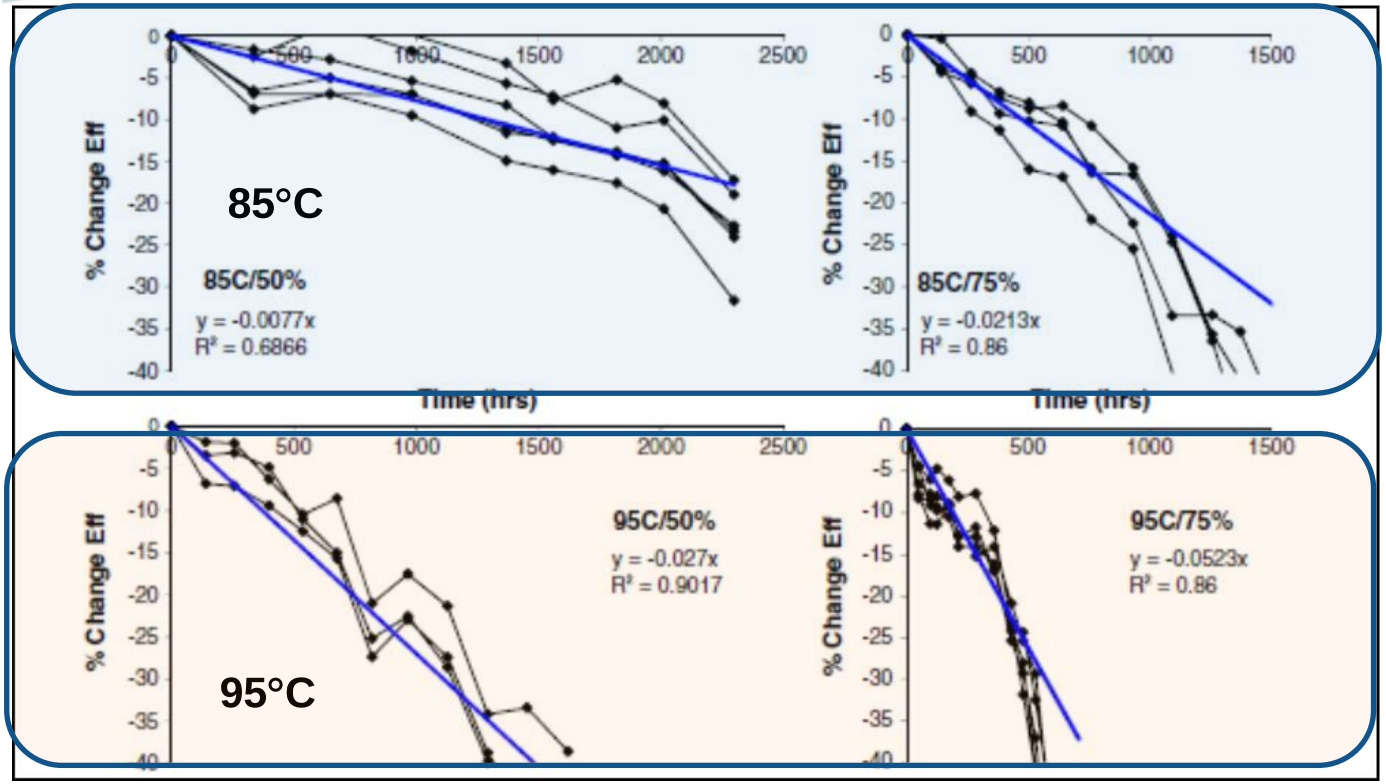


Humidity freeze and Temperature cycles with no humidity shows similar changes in performance.

<u>Future experiments</u>

Isolate Temp. and Moisture and perform indoor tests with and without light to understand electrical performance and compare the results with outdoor performance

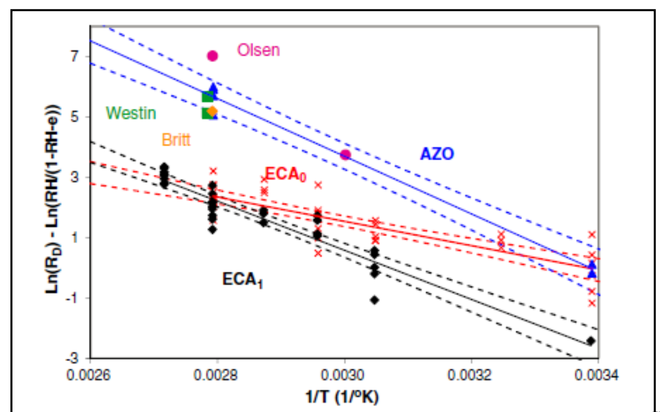
Indoor ALT's – Stress conditions- Multiple failure modes



Temperature and Humidity effects

Combinations of different T and RH

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

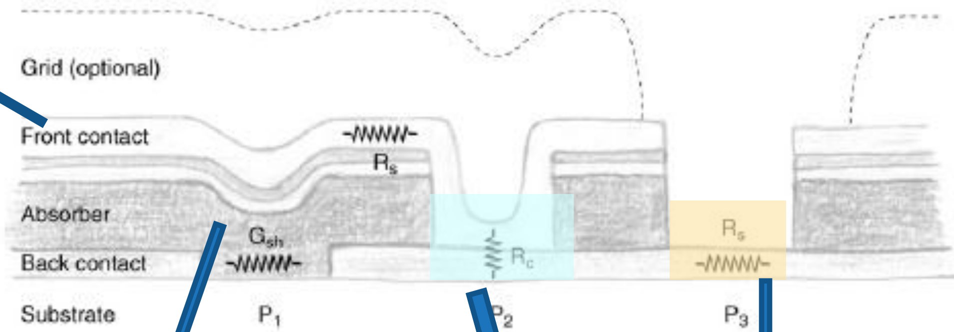


Need to interpolate the results to use condition
D.Coyle et.al PVMRW 2010

Interconnect degradation Failure modes/mechanisms

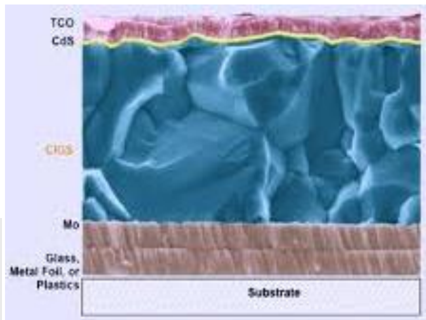
CC of ZnO:Al decreases
Affects FF (high ohmic losses in Front contact)

Monolithically interconnected cells



ABSORBER

J-V parameters
Voc , FF



Sheet resistance
Mo-P3 scribe

Performance loss

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

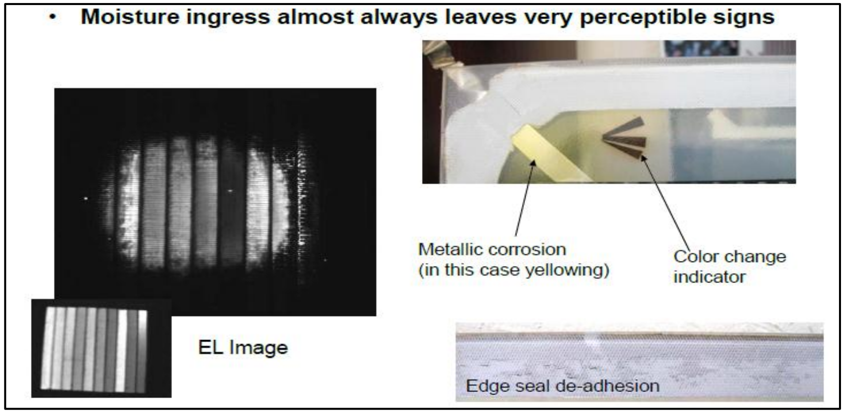
Resistance
P2 contact resistance
(Mo and ZnO:Al)

CIGS absorber

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 (Ω/□)	10	20	30
Mo back contact sheet resistance (Ω/□)	0.5	0.7	1
CIGS absorber resistivity (Ωcm)	20	10	10
P_2 contact resistance (Ωcm^2)	$\sim 10^{-4}$	$\sim 10^{-3}$	$\sim 10^{-3}$
Mo sheet resistance in P_3 (Ω/□)	0.5	100	∞

Solar Energy Materials & Solar Cells 75 (2003) 47–55

Finger prints-outdoor metrology & modeling

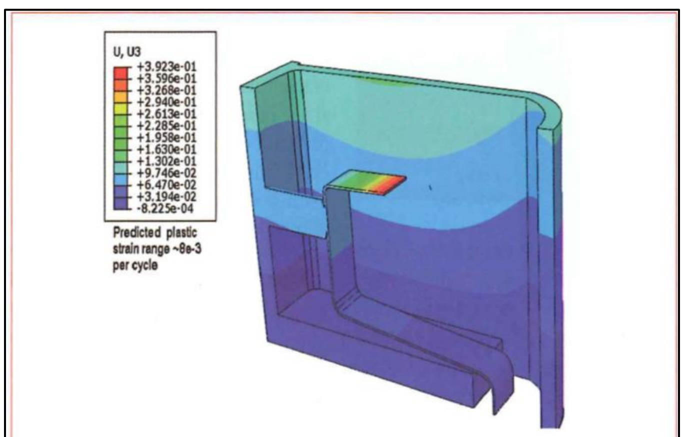


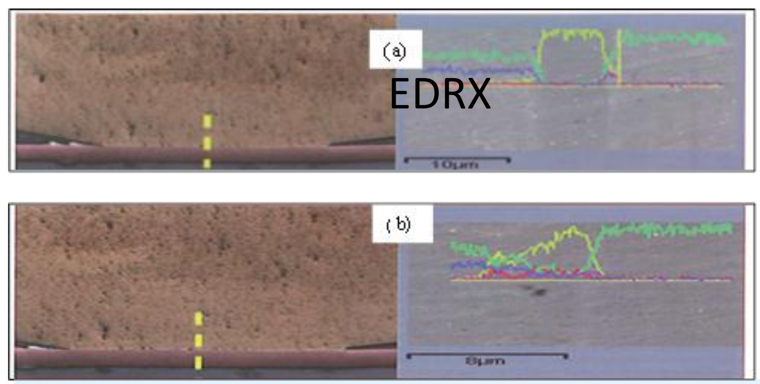
Common Failure Modes for Thin-Film Modules and Considerations Toward Hardening CIGS Cells to Moisture -A "Suggested" Topic Kent Whitfield, Dir. Reliability

Outdoor metrology Finger prints

Failure mode and effect analysis Junction box, potting and busbar – stress/strain amplitude

Establishing a reliability methodology for thermal- cycle failure modes for CIGS modules-Kent Whitfield et.al.





Correlation of metalling mixing corresponds to bond strength at the weld. a)Sharp b)smooth transitions in metal mixing

Welded joints analyzed using EDRX measurements .

"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"

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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

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THANK YOU FOR YOUR ATTENTION!