

# Striving for a standard protocol for preconditioning or stabilization of polycrystalline thin film photovoltaic modules



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# Outline of Talk

- ❑ Rationale for stabilization/preconditioning procedure
- ❑ Proposed Study plan to probe transitory behavior
  - Consists of preconditioning
  - Dark 90°C anneal at open circuit
    - ❖ emulates 85/85, but shorter and perhaps induce reversible changes
  - Two branches of subsequent stabilization
    - ❖ Light exposure at 1-sun, 60°C
    - ❖ Dark exposure at 60°C, in forward bias between optimum power point voltage and open-circuit voltage
- ❑ Modules used in study
- ❑ Value of C-V profiling as signature
- ❑ C-V profiles
  - on CIGS module, sweep directions, frequencies
  - Carrier concentrations, depletion widths on CIGS & CdTe modules
- ❑ Performance changes in CIGS & CdTe modules with stabilization/preconditioning procedure
- ❑ Summary & conclusions
  - CV -derived depletion width changes & hysteresis appear linked to stability
  - Dark exposure in forward bias likely emulates light exposure at 1-sun

# Rationale for Preconditioning Procedure

- ❑ Transient and metastable changes in CdTe/CIGS performance pose challenges in assessing performance:
  - Is a unique PV conversion efficiency/performance metric possible without specifying prior exposure history? (probably not)
  - Time between exposure and I-V measurement is critical
  
- ❑ Current standard for thin-film PV certification (IEC 61646) stabilization:
  - calls for light-soaking until change in power  $\leq 2\%$  is achieved, after consecutive periods of at least  $43 \text{ kW-h/m}^2$  of integrated irradiance
  - designed with amorphous silicon (a-Si) in mind
    - ❖ Dominant defect mechanism in a-Si: light-induced Staebler-Wronski effect
  - CIGS or CdTe devices most likely have different defect mechanisms
    - ❖ Current procedure may be inadequate when applied to CIGS / CdTe
  
- ❑ Appropriate preconditioning or stabilization steps prior to performance testing would lead to reduced error in assessing long-term energy yield, service lifetime and/or reliability.

# Defects in CIGS or CdTe

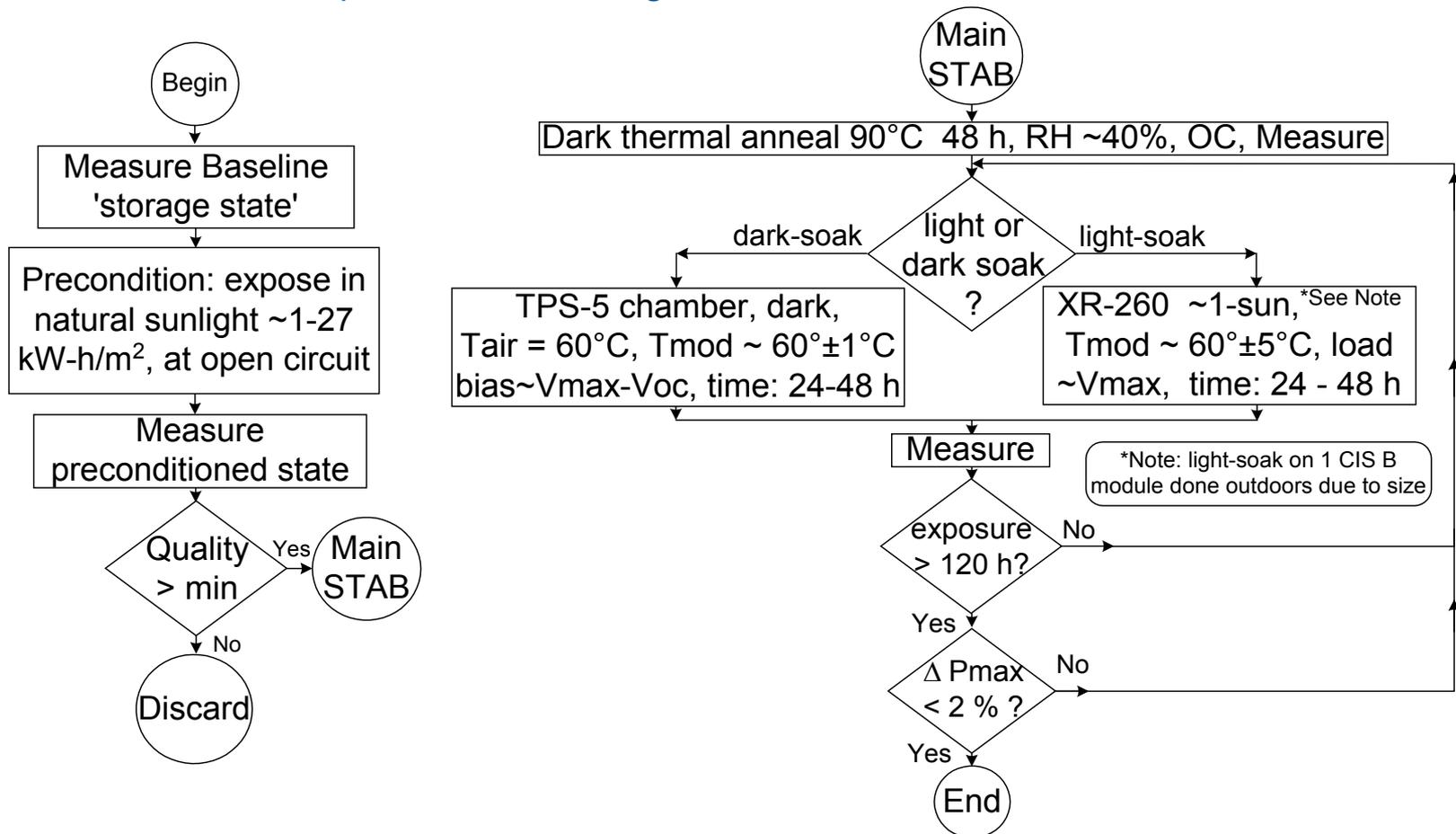
- ❑ Ascribed major role in shaping transient or metastable phenomena
- ❑ Mobile ions
  - CdTe
    - ❖ Cu moving between back contact and CdS/CdTe interface
  - CIGS
    - ❖ Cu - In vacancy complexes
    - ❖ Se vacancy
- ❑ Presence of Traps
  - CdTe
    - ❖ Voc increases with time
  - CIGS
    - ❖ Persistent photoconductivity
    - ❖ Changes in acceptor concentration after thermal anneal
    - ❖ Charging/discharging of donors at CdS/CIGS interface
- ❑ C-V profiling used as probe for defects in CIGS & CdTe

# Proposed Stability Study Plan Flowchart

## □ Preconditioning step & Main Stabilization Sequence Study Plan

### ➤ Main Stabilization:

- ❖ dark 90°C anneal step, emulates and is shorter version of 85C/85% RH 1000-h certification test
- ❖ consists of two branches: light exposure & biased dark exposure, both @ 60°C
- ❖ Biased dark exposure is advantageous if successful because of ease and lower cost



# Modules Studied

- Diverse set of CdTe & CIGS modules
  - Some nascent or new, never used, or stored as controls
  - Some pre-exposed in hot-humid climate
  - Some light-soaked indoors

Module Type	Quantity	Exposure Conditions	Pre-existing exposure conditions
CdTe A	2	One each: light soak, biased dark soak	Yes, hot-humid outdoors 3 years
CdTe B	2	One each: light soak, biased dark soak	No, nascent
CdTe C	1	biased dark soak	Yes, indoor light-soak, 1130 kW-h in 2002
CIGS A	4	Two each: light soak, biased dark soak	Nascent: 3 controls from 2003; 1 pre-exposed in hot-humid outdoors 3 years
CIGS B	2	One each: light soak, biased dark soak	No, nascent

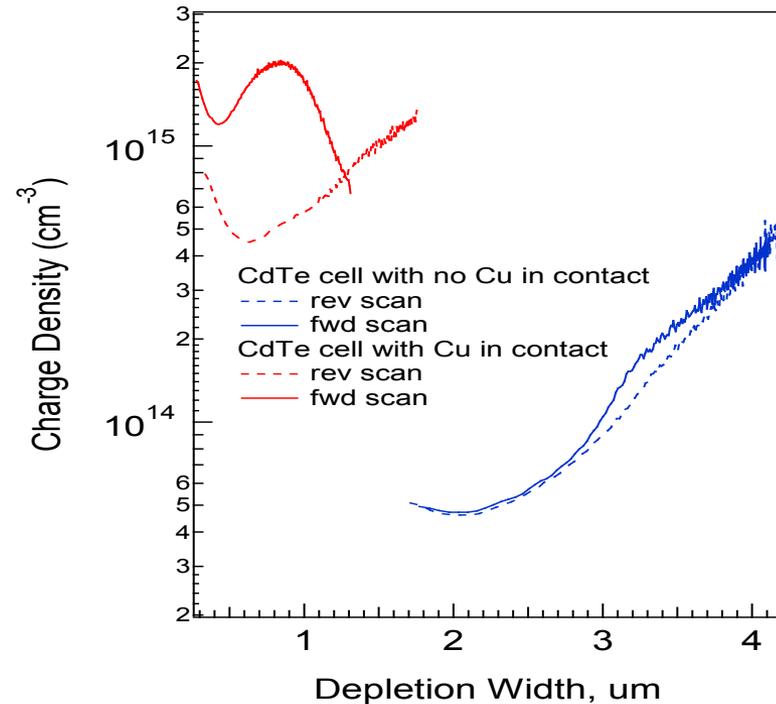
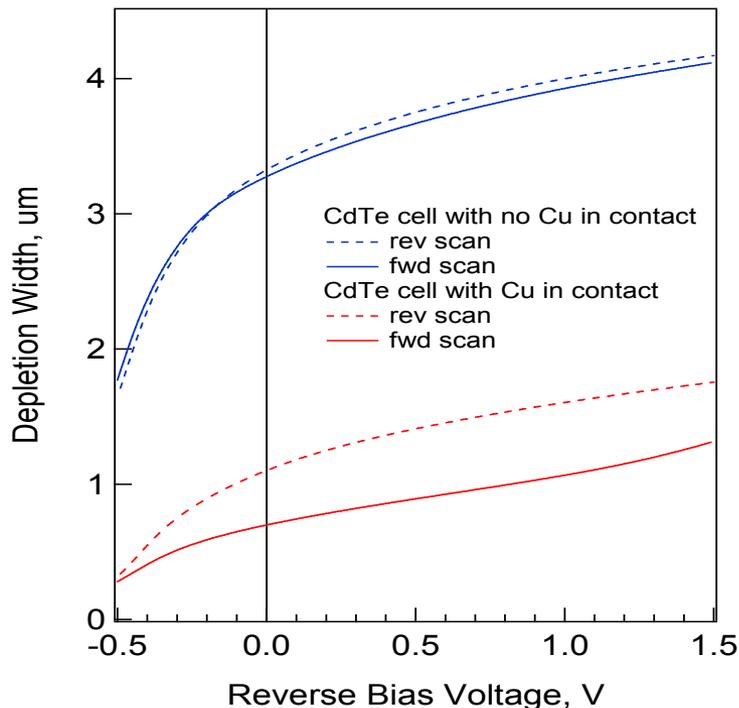
# Module characterization tests

- I-V
  - Using large area continuous solar simulator (LACSS) apparatus
  - Dark & light (STC), part into reverse bias
    - ❖ Derive series resistances, shunt conductances, etc..., via standard diode analysis
- C-V profiling
  - Used precision HP 4284A LCR meter
  - If module cells are uniform, measuring C-V on module with  $N_c$  number of interconnected cells, produces signal as if the device under test were a cell sized  $0.5\text{-}3\text{ cm}^2$ ,
    - ❖ due to series connection & magnitude cancellation of cell area ( $A_c$ ) & number ( $N_c$ )

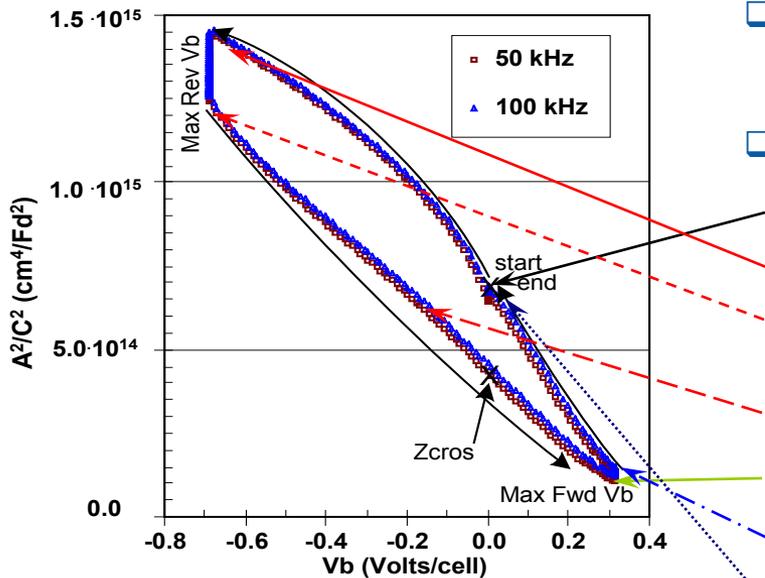
$$\frac{1}{C_{Mod}} = \frac{1}{C_1} + \frac{1}{C_2} + \dots + \frac{1}{C_j} \dots + \frac{1}{C_{N_c-1}} + \frac{1}{C_{N_c}} \Rightarrow C_{Mod} \approx \epsilon \cdot \epsilon_0 \cdot \frac{1}{w_D} \cdot \frac{A_C}{N_C} \quad (1)$$

# Value of C-V profiling CdTe cells

- Albin, D.S. et al., “Degradation and Capacitance-Voltage Hysteresis in CdTe Devices,” *ibid. these proceedings*.
- Hysteresis in depletion width vs. bias and derived carrier densities as one sweeps into reverse then up to forward bias appears correlated to amount of Cu in devices
  - No Cu in back contact  $\Rightarrow$  little hysteresis in C-V profile
  - Cu in back contact  $\Rightarrow$  hysteresis in depletion width between reverse & forward bias scans



# C-V profiling on CIGS Module



- Mott-Schottky plot upper graph

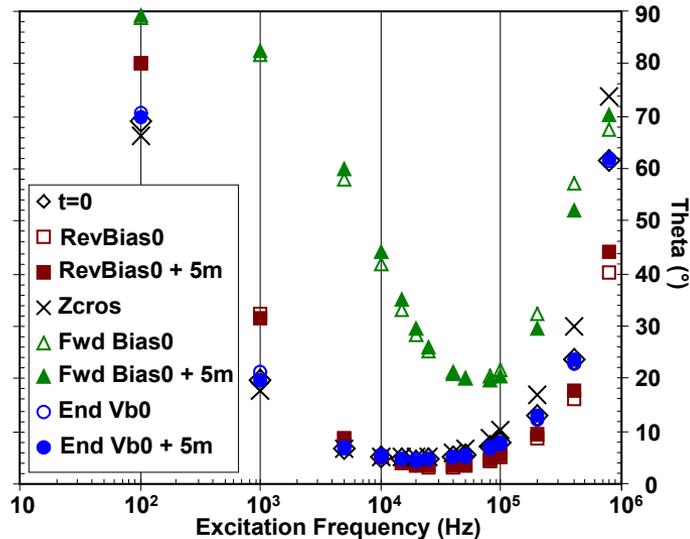
- $A^2/C^2$  vs.  $V_{bias}$

- C-V scan sweep details

- Start  $V_b = 0$
  - sweep to reverse bias, arrives at extrema
  - $V_b$  dwells 5 mins. at extrema in reverse
  - sweep reverses to forward bias
  - $V_b$  arrives at max fwd bias
  - $V_b$  dwells 5 mins. at max fwd bias
  - sweep reverses & scans down to 0
  - dwell for 5 mins. at 0 bias

- Multiple C-V profiles run across broad span of frequencies 100 Hz-800 kHz, (lower graph) to determine location of best signal

- best signal range ~ 50 – 100 kHz is  $\Theta \leq 20^\circ$
  - $\Theta$  = angle between reactive component & total Z vector = arctangent of dissipation



# CIGS A module, biased dark exposure branch: carrier density & depletion width

□ Depletion width ( $W_d$ ) vs.  $V_{bias}$  upper graph & carrier density ( $N(W_d)$ ) lower graph shown

➤ Profiles at various stages of exposure: baseline, after precondition, after dark 90°C anneal, after 2 voltage-biased dark soaks

❖  $W_d$  profiles show variation & hysteresis

➤  $W_d$  hysteresis between measurements sweeping into reverse bias & then forward bias

❖ ~16%-20% varying by exposure,

❖ large increase in  $W_d$  and hysteresis after dark 90°C anneal

□  $N(W_d)$  Carrier densities

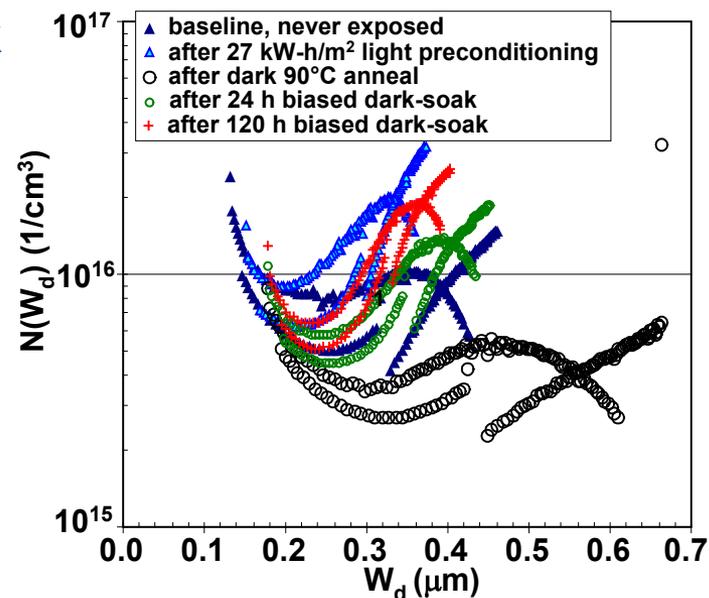
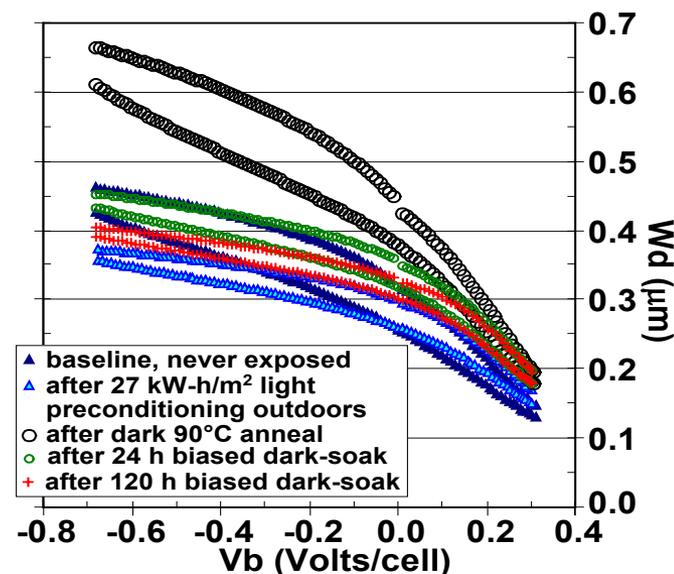
➤ At baseline start near  $\sim 10^{16}/\text{cm}^3$

➤ Increase preconditioning outdoor exposure

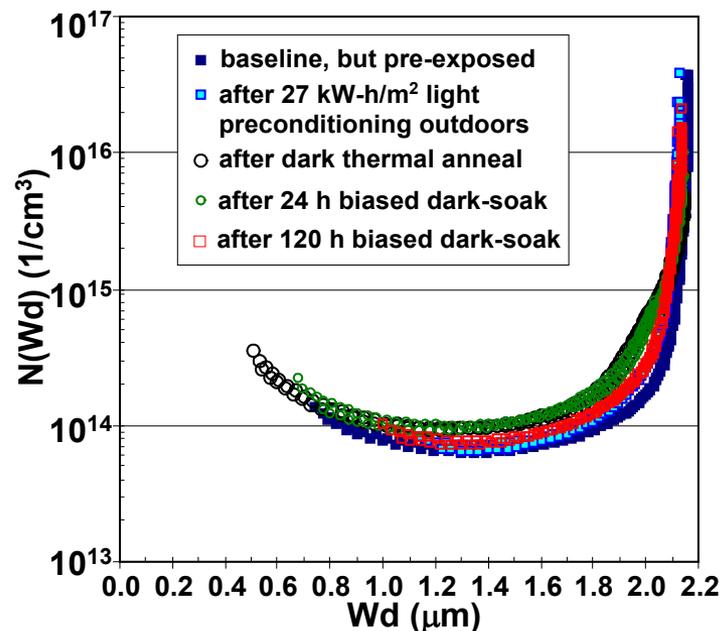
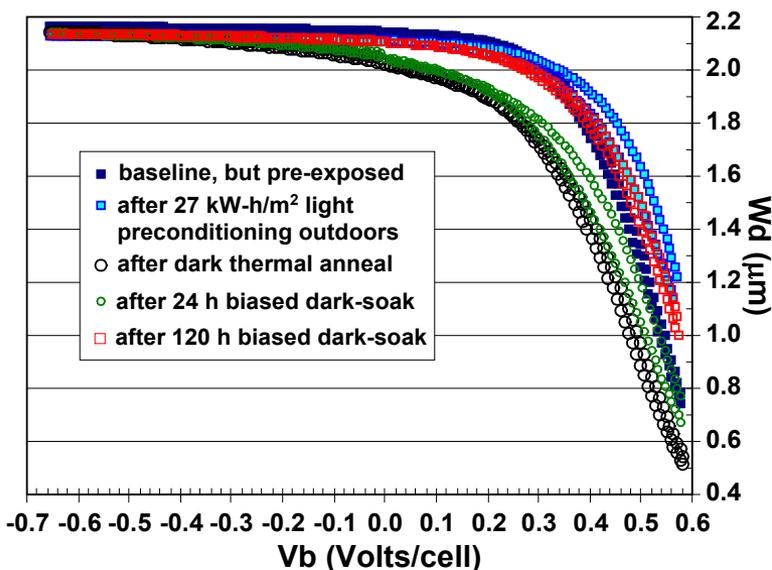
➤ Collapse after dark 90°C anneal

➤ Increase after 120 h biased dark soak 60°C back up to level after preconditioning exposure

□ Similar changes for light-soaked CIGS A



# CdTe C module, biased dark exposure branch: carrier density & depletion width



- Depletion width ( $W_d$  vs.  $V_b$  upper graph) & carrier density ( $N(W_d)$  lower graph) shown
  - Profiles at various stages of exposure, as in previous dark-soak example
- $W_d$  profiles
  - Show less hysteresis ~5%-15% of total  $W_d$  and/or variations (as %) than CIGS during tests
  - larger & span larger range than for CIGS
  - Dark 90°C anneal lowers  $W_d$
  - Post-anneal exposure brings profiles close to levels after preconditioning
- $N(W_d)$  carrier densities
  - show small or modest variation with exposure and dark anneal
  - Minima ~just under  $10^{14}/\text{cm}^3$ , consistent with Albin data for device with no Cu

# CdTe A or B, light/dark exposure branches, depletion & carrier densities summarized, compared to CdTe C

## □ CdTe A

### ➤ Depletion widths ( $Wd$ )

- ❖  $Wd$  vs.  $Vb$  profile changes and hysteresis are smallest of all CdTe
- ❖ little changes on dark 90°C anneal
- ❖ subsequent exposures (light/dark) bring  $Wd$  vs.  $Vb$  profiles close to where they were at baseline

### ➤ Carrier densities

- ❖ similar minima ~just under  $10^{14}/\text{cm}^3$
- ❖ mostly similar to B except spanned  $Wd$  is less than B modules

## □ CdTe B

### ➤ Depletion widths ( $Wd$ )

- ❖  $Wd$  vs.  $Vb$  profiles show variations & hysteresis similar to C
- ❖ somewhat larger than A
- ❖ exhibit similar changes with dark 90°C anneal:
  - ✓  $Wd$  values lowered, span vs.  $Vb$  larger
- ❖ subsequent exposures raise & bring  $Wd$  vs.  $Vb$  profiles close to levels observed after preconditioning

### ➤ Carrier densities

- ❖ similar minima ~just under  $10^{14}/\text{cm}^3$
- ❖ mostly  $10^{14}$ - $10^{15}$ , for  $Wd$  0.8-2  $\mu\text{m}$
- ❖ Show similar variation with exposure
- ❖ dark 90°C anneal has modest effect

# Performance changes in CIGS A or B modules due to stabilization procedures

□ I-V Changes plotted relative to baseline vs. 9 exposure categories

□ initial preconditioning outdoor exposures increase performance of A1-A3, slightly drops that of B1,B2

□ dark 90°C anneal substantially degrades performance ~5%-12%, largely due to FF & Voc losses

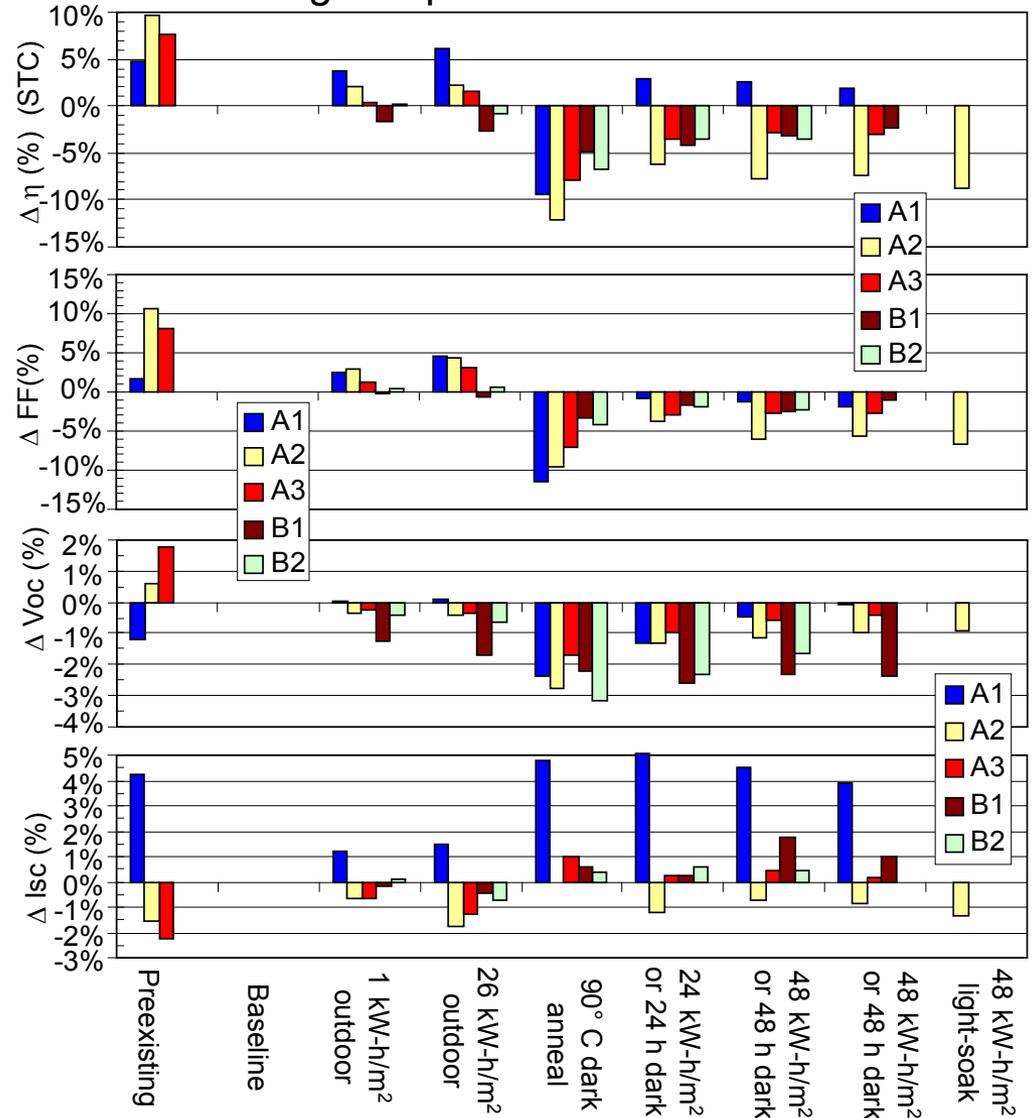
□ Subsequent light/dark soaks only mitigate losses from dark anneal  $\leq 1/2$

□ Performance appear moderately stabilized after 3 exposures

➤  $\Delta \eta_{STC} < \sim 2\%$  after 3 exposures post dark anneal

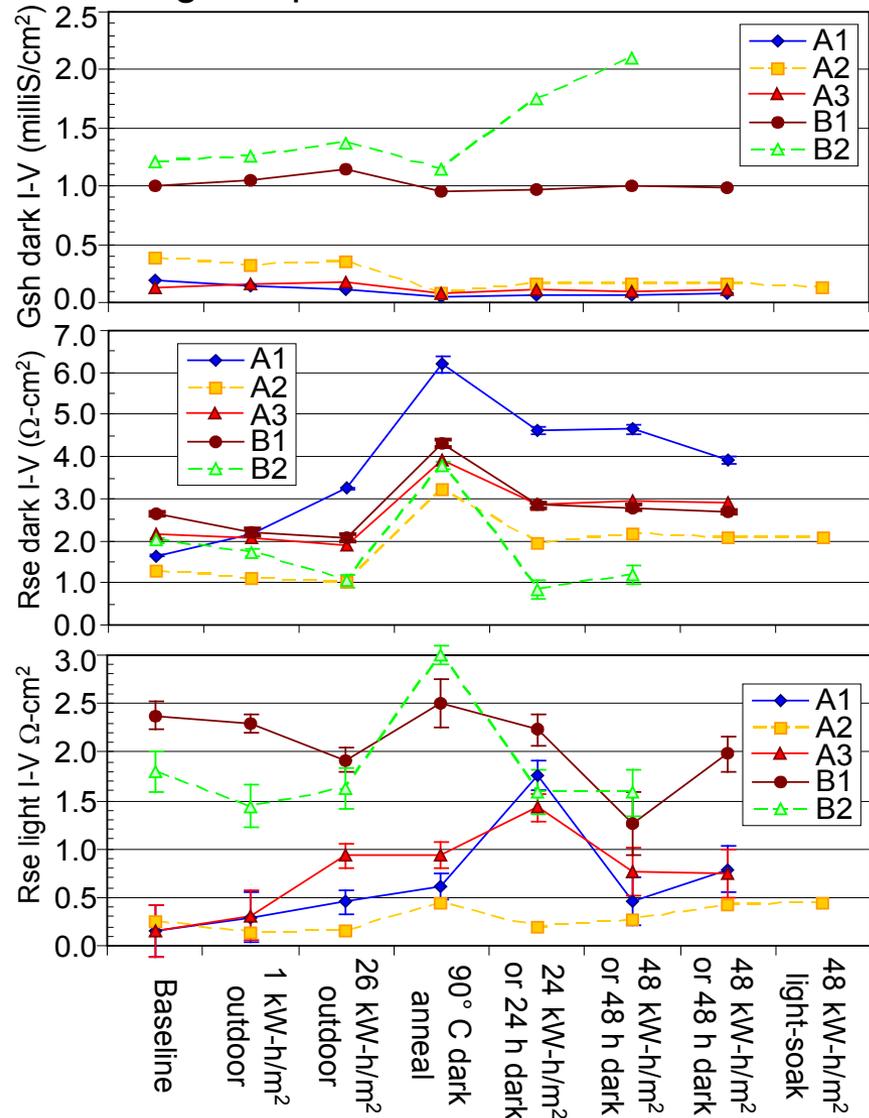
➤ Light or dark exposures appear equally capable of driving toward stabilized  $\eta_{STC}$

Module odd/even numbers & dark/light colors  
 ⇔ dark/light exposures after dark 90 C anneal



# Sources of performance changes in CIGS A or B modules due to stabilization procedures scrutinized

Module odd/even numbers & dark/light colors  
 ⇄ dark/light exposures after dark 90 C anneal

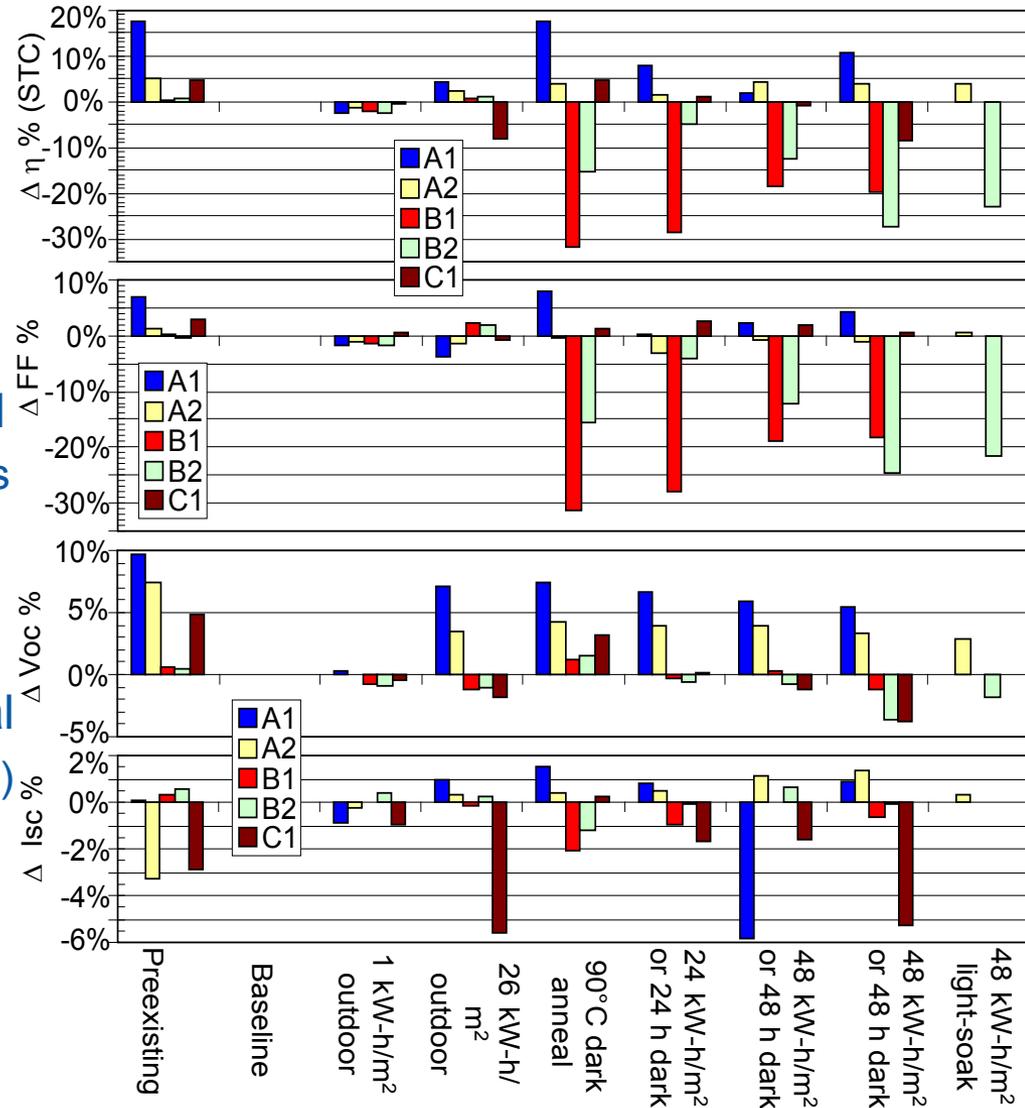


- Std. diode analysis for series resistance (Rse) & shunt conductance (Gsh)
- CIGS A
  - Rse dark/light increase after dark anneal,
    - ❖ Rse (dark) drop in subsequent exposures, but stay somewhat elevated
    - ❖ Rse (light) diminish in latter exposures, are fairly low at end (0.4-0.8 Ω-cm²)
  - Gsh are relatively small and drop after dark anneal and all exposures
- CIGS B
  - Rse dark/light increase slightly or modestly after dark 90°C anneal, but diminish in subsequent exposures
  - Gsh increase for exposures after dark anneal for B2, but B1 shows no change after all exposures after dark anneal
    - ❖ somewhat larger than for CIGS A, may be more of source of FF loss

# Performance changes in CdTe A, B, C modules due to stabilization procedures

- ❑ Changes plotted relative to baseline
- ❑ initial preconditioning outdoor exposures result in small changes
- ❑ dark 90°C anneal
  - degrades performance of B's due to FF
  - recovers performance of A & C
  - increases Voc for all modules
- ❑ exposures subsequent to dark anneal
  - keep A1,A2 gains in dark/light exposures
  - B1 improves in dark soak, B2 improves at 1<sup>st</sup> then degrades in light soak
  - C1 slowly loses gains in dark-soak
- ❑ Performance ( $\Delta\eta_{STC}$ ) post dark anneal
  - A2, B1 moderately stabilized ( $\Delta\eta_{STC} < 2\%$ ) after 3 exposures
  - rest not stabilized ( $\Delta\eta_{STC} > 2\%$ )
  - dark exposures appear no worse than, & are equally capable of driving toward stabilized  $\eta_{STC}$  as light exposures

Module odd/even numbers & dark/light colors  
 ⇔ dark/light exposures after dark 90 C anneal



# Sources of performance changes in CdTe A, B, C modules due to stabilization procedures scrutinized

Module odd/even numbers & dark/light colors

↔ dark/light exposures after dark 90 C anneal

□ Std. diode analysis for Rse & Gsh

□ all CdTe modules exhibit very low Gsh  
 ➤  $\leq 0.2$  milliS/cm<sup>2</sup>, Gsh not a problem at all

□ Rse dark/light

➤ CdTe A:

- ❖ either slight change or increase initially
- ❖ drop close to baseline or lower with subsequent exposures

➤ CdTe B

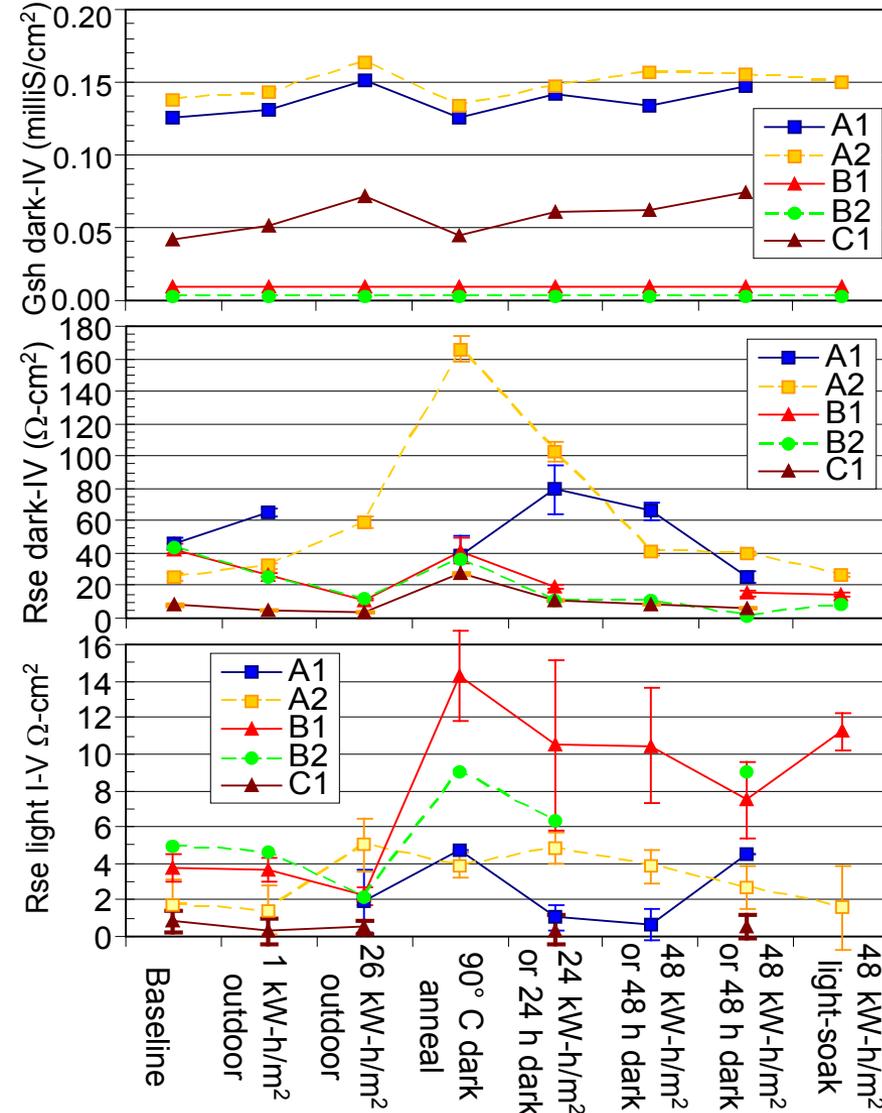
- ❖ Rse (light) increase dramatically after dark anneal & stay high in subsequent exposures

➤ CdTe C

- ❖ Rse not a problem

✓ Rse dark increase after dark anneal but drop to lower than baseline in subsequent exposures

✓ Rse light stay low ( $\leq 1$  Ω-cm<sup>2</sup>) throughout tests



# Summary

## □ CIGS A & B (unexposed previously)

### ➤ FF losses dominate

- ❖ R<sub>se</sub> increases are chief cause for loss in CIGS A,
  - ✓ reversible in exposures (light-soak and biased dark-soak) after dark 90°C anneal, so hard to reconcile that with TCO degradation
  - ✓ more consistent with in changes in semiconductor as shown by changes in C-V carrier densities during tests
- ❖ R<sub>se</sub> increases observed in CIGS B, appear somewhat reversible in subsequent exposures
- ❖ Shunt losses likely more of problem for CIGS B
- Voc losses also present for both A & B, ~2%-4%
- Changes in and hysteresis in depletion width (C-V) suggest link to stability in CIGS A
  - ❖ not enough data measured for CIGS B

# Summary

## □ CdTe A (pre-exposed)

- Relatively stable during tests,
- modest increases in performance after dark anneal and subsequent exposures
  - ❖ but efficiencies are always lower than for CdTe B even after CdTe B degraded
- Voc increases after dark anneal
- relative small changes in depletion width and hysteresis thereof during exposure tests is consistent with link to stability

## □ CdTe B (unexposed)

- FF losses dominate after dark 90°C anneal
  - ❖ R<sub>se</sub> (light) increases appears likely main mechanism
    - ✓ do not reverse substantially in subsequent exposures, maybe irreversible changes after dark 90°C anneal at OC
  - ❖ efficiencies are fairly larger than CdTe A even after degradation
- larger changes in depletion width and hysteresis thereof during exposure tests consistent with link to stability

## □ CdTe C (pre-exposed)

- Slight FF, Voc increases with dark anneal & first few subsequent exposures
- I<sub>sc</sub> & Voc losses in latter exposures drop overall performance slightly
- modest changes in depletion width and hysteresis thereof during exposure tests are somewhat consistent with the stability- depletion width link

# Conclusions

- Devised stabilization / preconditioning study plan procedures that show promise in arriving at more stable performance values when implemented
  - Both types of exposure: light soaking at 1-sun & 60°C and voltage-biased dark-soaking at 60° C appear capable at driving similar performance changes for CdTe & CIGS
    - ❖ Have yet to more precisely quantify equivalency of exposure times between two types that produce stabilized performance values
  - C-V profiling and derived depletion widths changes plus hysteresis thereof likely provide valuable co-signature to potential metastability
    - ❖ details of hysteresis and link to stability is likely different for CdTe and CIGS

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