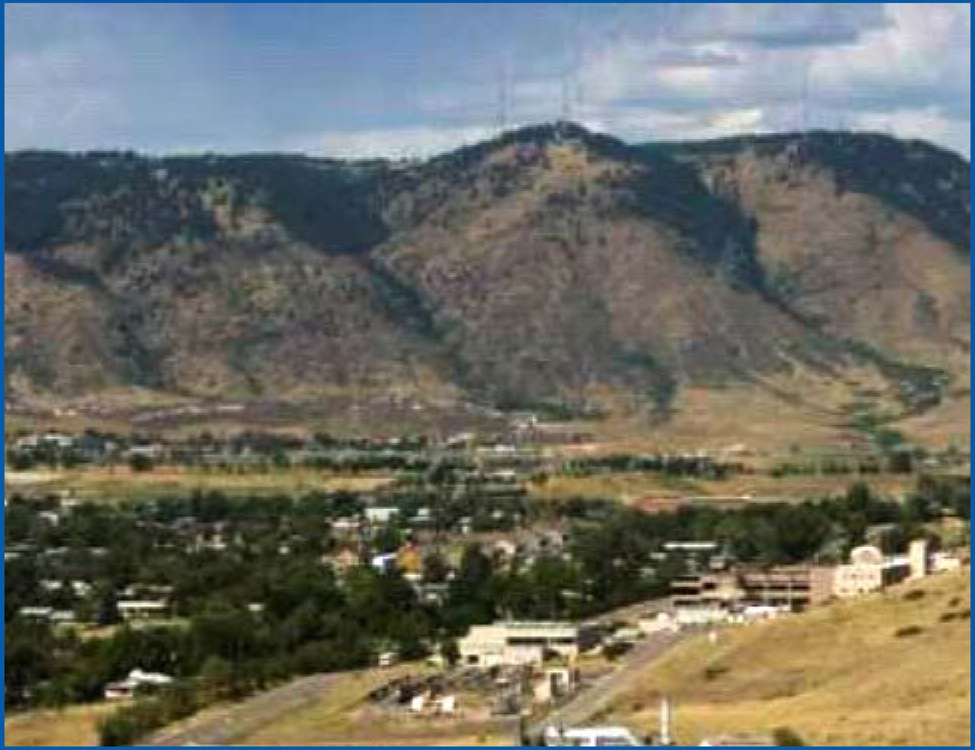
National Renewable Energy Laboratory

Innovation for Our Energy Future

Comparison of injection of carriers through light soaking and forward bias in dark (In Stabilization of polycrystalline thin film photovoltaic modules)



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February 19, 2010
Reliability Workshop
Denver West Marriott

Testing, Evaluation and Reliability Team

Outdoor Test Facility (OTF)

Outline

- Rationale: Metastability of CIGS & CdTe
- Study plan to probe metastable behavior
- Modules used in study
- Value of C-V profiling as signature
- C-V profile data
  - Carrier concentrations, depletion widths on CIGS & CdTe modules
  - 1 of each that went dark ⇨ light & light ⇨ dark
- Performance changes in CIGS & CdTe modules with exposure
- Summary

Rationale: Metastability of CIGS & CdTe

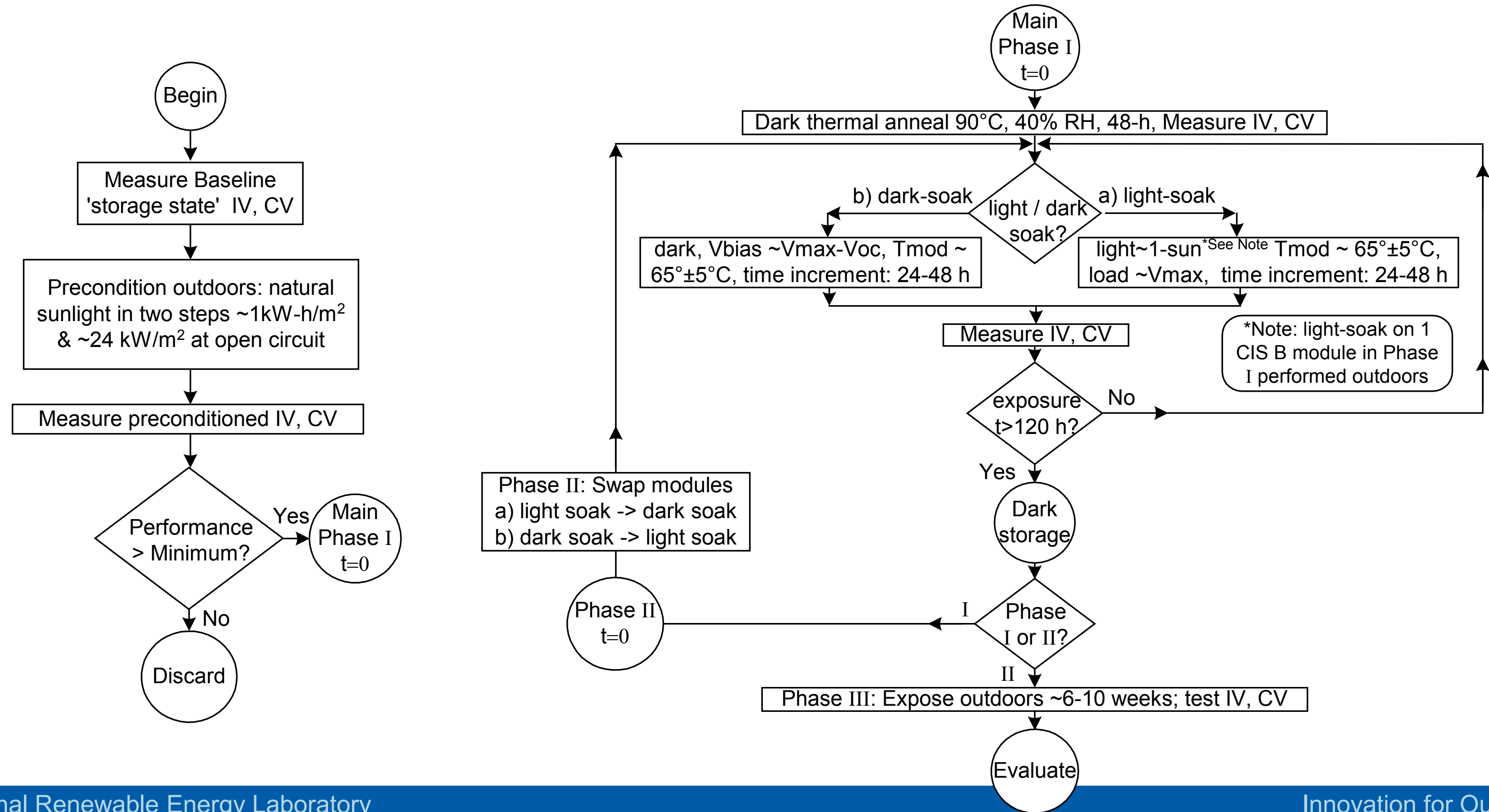
- High Performing CdTe & CIGS PV exhibit transient/metastable changes in performance that pose challenges in assessing accurate performance:
  - prior exposure history, time between exposure and I-V measurement critical

- Current standard for stabilization in thin-film PV certification (IEC 61646):
  - Light-soaking until change in power ≤ 2% is achieved, after successive periods of at least 43 kW-h/m^2 of integrated irradiance
  - designed for amorphous silicon where defect mechanism is light-induced Staebler-Wronski effect
  - CIGS or CdTe devices most likely have different defect mechanisms
    - current procedure probably inadequate for CIGS or CdTe (e.g. ions)

- Beckons preconditioning / stabilization steps prior to performance testing
  - reduced error in assessing consistent performance and
  - impacts accuracy of models for long-term energy yield, and/or reliability.

Preconditioning /Stabilization Study Plan

- Preconditioning steps:
  - ascertain minimum quality, emulates NREL preconditioning prior to IV measurements STC
- Main Stabilization Sequence: Phase I and II
  - dark 90°C anneal, emulates a short version of 85C/85% RH, 1000h certification test
  - consists of two branches: light exposure & biased dark exposure, both ~65°±5°C
  - Biased dark exposure is advantageous if successful because of ease and lower cost
  - Swap light/dark-soak modules in Φ–I ⇔ dark/light-soak modules Φ–II , no dark anneal



Modules Studied

- Diverse set of CdTe & CIGS modules
  - Some nascent or new, not used, or stored as controls
  - Some pre-exposed outdoors
  - Some light-soaked indoors
- All (except CIGS B) are glass(substrate/superstrate)/glass monolithically interconnected

Module Type	Quantity	Configuration	Pre-existing exposure conditions
CdTe A	2	Glass-superstrate-glass laminate, monolithically interconnected	Yes, outdoors 3 years
CdTe B	2	Glass-superstrate-glass laminate, monolithically interconnected	No, nascent
CdTe C	1	Glass-superstrate-glass laminate, monolithically interconnected	Yes, indoor light-soak, 1130 kW-h in 2002
CIGS A	3	Glass-substrate-glass laminate, monolithically interconnected	Nascent: 3 controls from 2003
CIGS B	2	Glass-flexsubstrate-glass laminate, solder bond interconnect	No, nascent

Module characterization tests

- I-V
  - Used large area continuous solar simulator (LACSS) apparatus
  - Dark & light (STC),

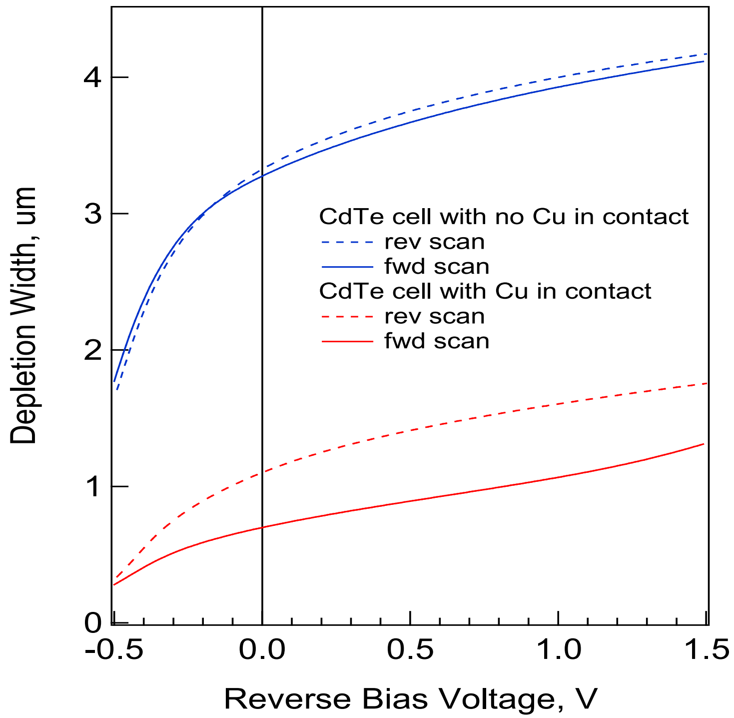
- C-V profiling
  - If module cells are uniform, measuring CV profile on module with N_C number of series cells each with cell area A_C, produces signal as if the device under test were a cell sized 0.5-3 cm^2, due to magnitude cancellation of A_C divided by N_C

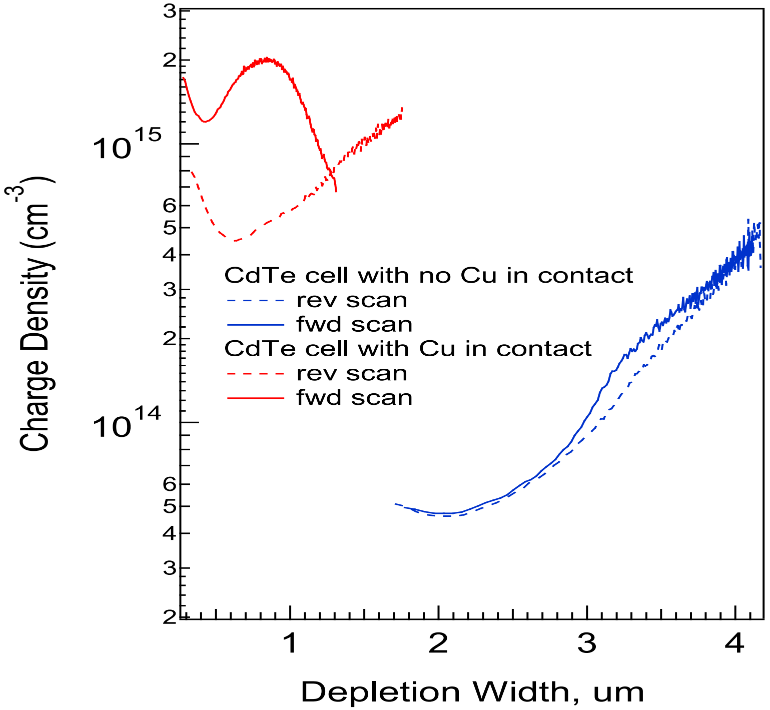
$$\frac{1}{C_{Mod}} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_j} \ldots + \frac{1}{C_{Nc-1}} + \frac{1}{C_{Nc}} \quad \Rightarrow \quad C_{Mod} \approx \varepsilon \cdot \varepsilon_0 \cdot \frac{1}{w_D} \cdot \frac{A_C}{N_C}$$

$$N(W_D) \quad = \quad \frac{2}{q\varepsilon\varepsilon_0} \cdot \frac{1}{d(1/C^2)/dV}$$ ⇔ Carrier density

Value of C-V profiling in CdTe devices

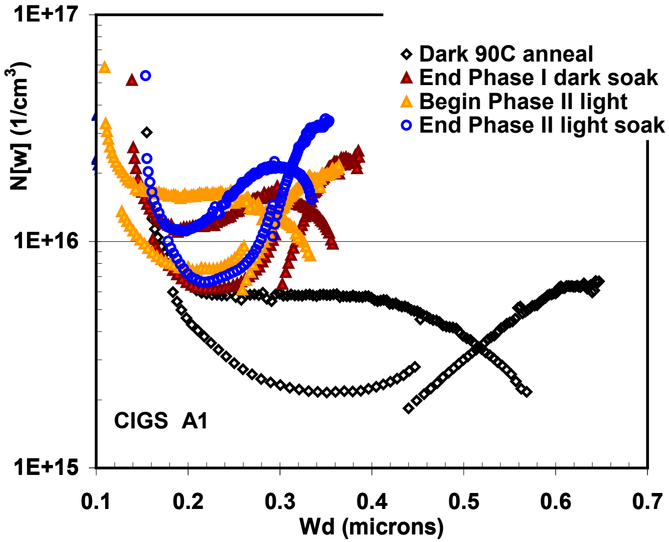
- Hysteresis & change in depletion width vs. bias ⇔signature to potential metastability
  - D. Albin et al., "Degradation and Capacitance-Voltage Hysteresis in CdTe Devices," paper 7412-18, Proc. SPIE 2009 Optics & Photonics Conf., San Diego, CA, Aug. 2009.
- depletion width and derived carrier densities as one sweeps into reverse then up to forward bias appears correlated to amount of Cu in devices
  - No Cu in back contact ⇨ little hysteresis in C-V profile, lower carrier densities
  - Cu in back contact ⇨ hysteresis in depletion width between reverse & forward bias

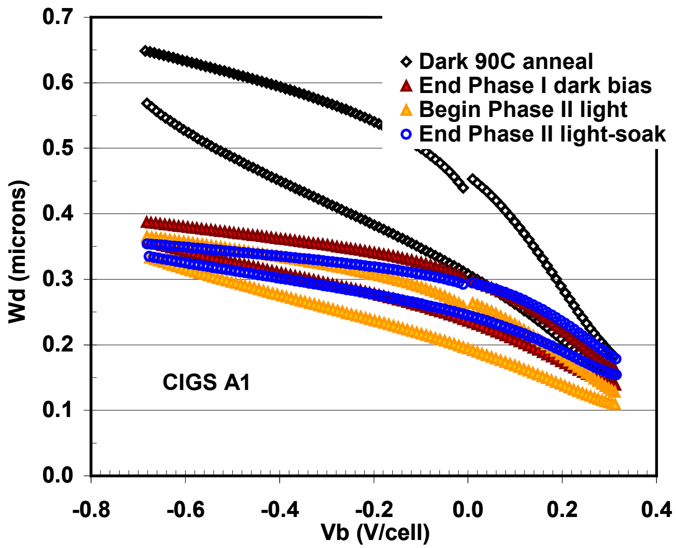




CV profiles CIGS A1: phase I dark soak ⇨phase II light soak

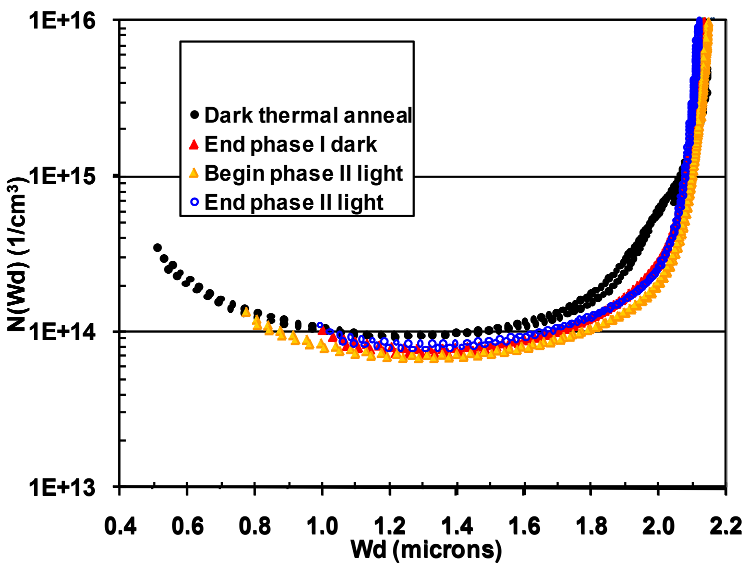
Carrier Concentration N(W) top, depletion width W_d bottom

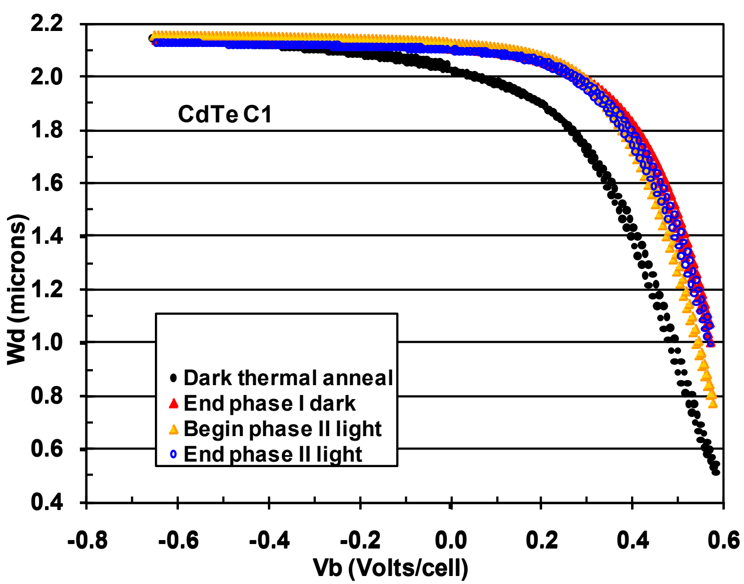




- Phase I (indoor dark soak)
  - Baseline, N ~ 1-3 $*10^{16}$
  - outdoor precondition 27 kW-h/m², slight shift of W_d upwards from baseline
  - dark anneal: drops N~2-7 $*10^{15}$, large shift up of W_d, large hysteresis ~50% at v=0
  - End of 3 dark soak steps (24h, 48h & 48 h)
    - restores N & Wd profiles closer to data after outdoor precondition, partway between precondition & anneal
- Dark storage ~ 3-4 months
- Phase II (indoor light soak)
  - Begin light soak after dark storage
    - N, Wd profiles relax slightly to state after outdoor precondition
  - End 3 light soak steps (48h, 30h & 48 h)
    - moves N, W_d data slightly between states after outdoor precondition and end of phase I

CV profiles CdTe C1: phase I dark soak ⇨ phase II light soak
Carrier Concentration N top, depletion width W_d bottom

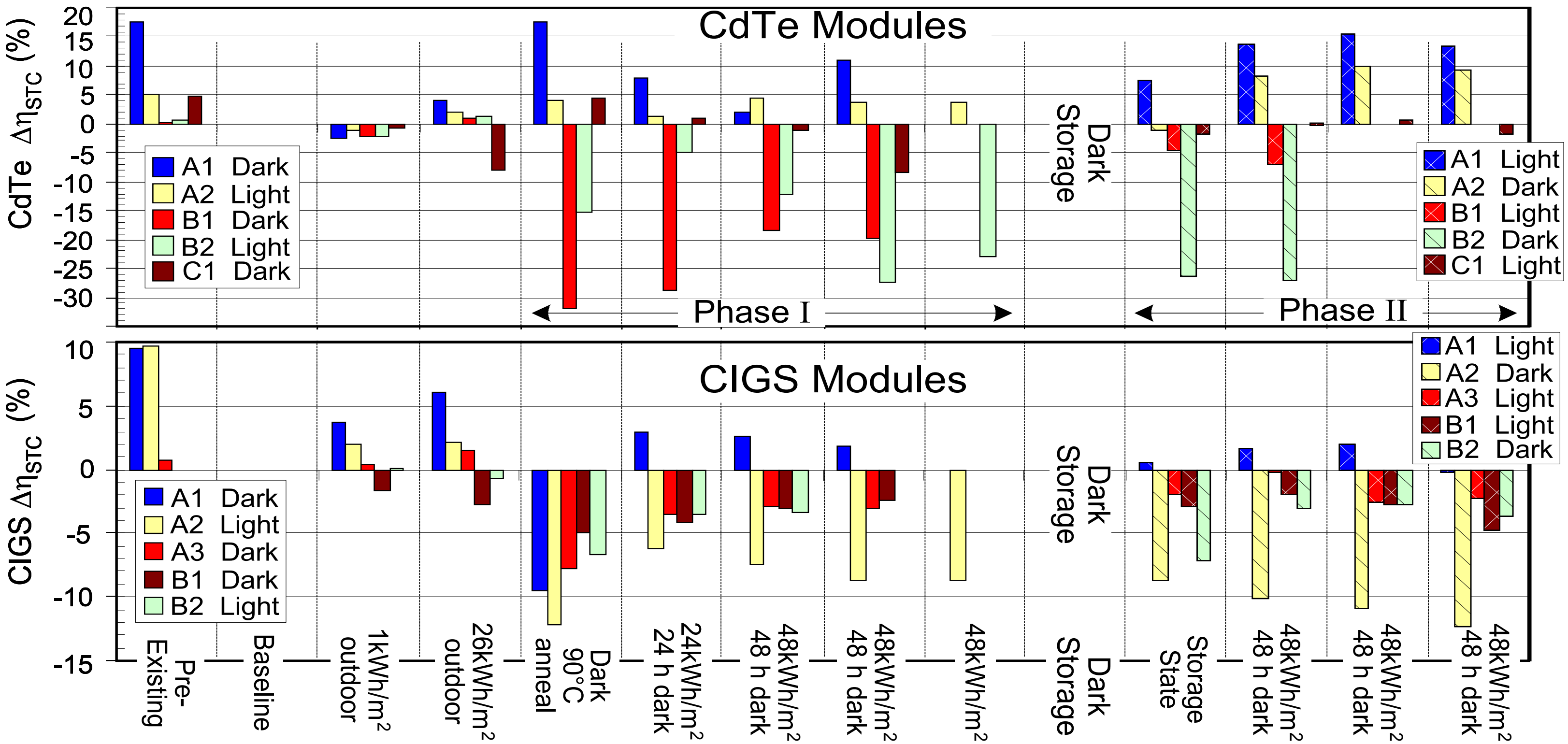




- Phase I (indoor dark soak)
  - Baseline, (valley) N ~ $7*10^{13}$-$1*10^{14}$
  - outdoor precondition 27 kW-h/m^2: some change in W_d upwards in forward bias, Δ N small
  - dark anneal: raises N~1-5 $*10^{14}$, large shift down of W_d, small hysteresis ≤5% at v>0
  - End of 3 dark soak steps: 24h, 48h, 48h
    - restores N close to outdoor precondition state,
    - W_d midway between baseline and outdoor state
- Dark Storage ~ 3 months
- Phase II (indoor light soak)
  - Begin light soak after dark storage
    - N, Wd profiles relax close to state at baseline
  - End 3 light soak steps (48h, 30h & 48 h)
    - returns N, Wd data profiles close to that just after end of phase I biased dark soak

Performance changes vs. exposure relative to baseline

- Phase I
  - Baseline = 0 Δ, some pre-existing higher
  - outdoor precondition 1 & 26 kW-h/m^2
    - CIGS A, CdTe A & B improve
    - CIGS B, CdTe C drop
  - dark thermal anneal
    - All CIGS + CdTe B drop,
    - CdTe A & C improve to preexisting performance
- Phase I (cont)
  - Exposures: 4 light /3 dark soak steps
    - CIGS seem to stabilize (Δ η ≤ 2%) in light or dark
    - CdTe mixed, some stabilize (B1, A2)
- Phase II swap: dark storage ~3-4 months
  - Some CdTe recover, CIGS change some
  - 3 light/dark steps 48 h each
    - CIGS mostly stabilize (Δ η ≤ 2%)
    - CdTe: type A stabilize as per pre-existing, C stabilizes near baseline, type Bs fail



Details of performance changes

- Dark thermal (90°C, 48h OC) anneal
  - CdTe A2, B1, B2 & all CIGS
    - FF loss is largest source of degradation
  - All CdTe Voc improve ~ 2%-8%
  - All CIGS Voc degrade ~ 2%-3%

- Biased dark soak phase I
  - V_{bias} chosen ~ halfway between Vmax & Voc,
  - I_{bias} <20% I_{max},
  - might have stifled stabilization

- Biased dark soak phase II
  - V_{bias} closer to Voc than phase I
  - I_{bias} ~ Imax
  - probably accelerated stabilization or changes in performance

Summary

- Polycrystalline CIGS & CdTe PV show metastable behavior in performance
- Implemented stabilization/preconditioning procedures using two types exposures light soak at 1-sun and voltage-biased dark-soak, at 65°±5°C
  - If stabilization is defined as $\Delta\eta \leq 2\%$ between successive increments
    - both (light/dark) capable of driving stabilization for most CdTe & CIGS modules
    - some modules did seem to behave differently with light vs. dark exposure
  - Capable of driving performance of CdTe back to incipient values before exposure
  - Biased dark exposure should be performed with setting $I_{bias} \sim I_{max}$ for acceleration
- IEC61646 stabilization defined as $\Delta\eta \leq 2\%$ between successive increments may be <u>inadequate</u> to ascertain actual stability in polycrystalline thin-film PV
- Will soon deploy same module set outdoors for 6-10 weeks to ascertain which one of light- or biased dark- exposures comes closest to outdoor stabilization performance level
- Will soon start testing newer CdTe & CIGS module set

Summary

- CV profiling:
  - Changes in depletion widths (Wd) & its hysteresis upon exposure or thermal anneal provide signature to metastability
  - Quantifiyng link to stability is likely different between CIGS and CdTe
  - For some modules CV / Wd profiles exhibit different behavior in light vs. dark exposure

Acknowledgements

- Dave Albin, for discussions & insight
- Steve Rummel, Allan Anderberg IV measurements