Light Soaking Effects on PV Modules: Overview and Literature Review

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Abstract

- Light exposure of PV modules can produce a variety of effects including reversible metastable phenomena which influence the accuracy of PV module power output determination and long-term phenomena which affect power output stability of installed modules.
- We present a brief review of technical literature on the effects of light exposure on different PV module technologies, including a-Si/μc-Si, CdTe, CIGS, and c-Si, addressing: the physical mechanisms of light-induced changes in each PV technology; long-term light-induced degradation effects; and current literature knowledge on PV module preconditioning for accurate power output determination.
- Our poster is intended to provide an overview and to promote discussion on these subjects amongst workshop attendees.

a-Si / μc-Si

Amorphous Silicon

- Typical device structure, Ref [1][A]
- Light-induced degradation (LID) causes ~10-30% efficiency loss in first several hundred hours of light soak, Ref. [2][B]
- IEC 61646 qualification test introduced extended duration light soak requirement for module stabilization
  - Light soak until power varies <2% in successive 43 kW-hr/m^2 periods
- Microcrystalline silicon (μc-Si) shows increasing level of LID depending on amorphous content, Refs. [3],[4]

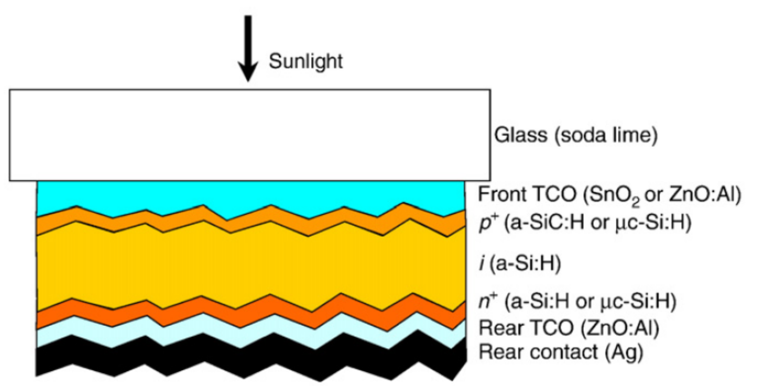
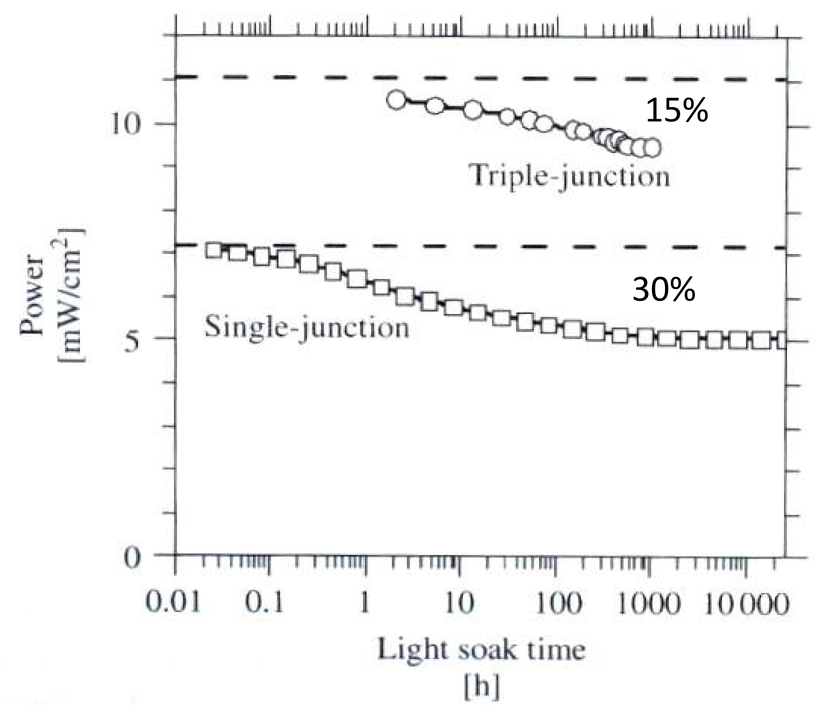


Fig. 1. Schematic of a state-of-art *p-i-n* a-Si:H solar cell on a glass superstrate.

From Ref. A



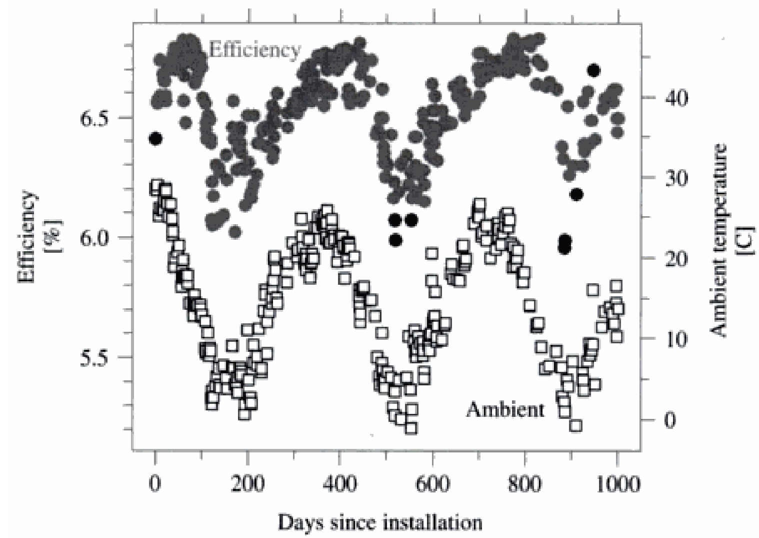
From Ref. B, page 511

Staebler-Wronski Effect in a-Si

- Staebler-Wronski effect (SWE)
  - Staebler and Wronski, 1977, Ref. [5]
  - Reduction in dark conductivity and photoconductivity of a-Si:H after light exposure
  - Reversible by annealing >150 C
- Mechanism, Ref. [6]
  - Recombination-induced breaking of weak Si-Si bonds by optically excited carriers after thermalization, producing defect centers that lower carrier lifetime
  - Self-limiting effect
- Details
  - Many proposals, but exact microscopic mechanism not fully understood
  - Intrinsic effect – does not depend on impurities, Ref. [7]
  - Occurs in bulk of material, with additional surface contribution, Ref. [6]
  - Defects introduced by e.g. current injection produce different results, Ref. [6],[8],[9]
  - Accelerated testing possible using high-intensity pulsed light, while maintaining standard operating temperature, Ref. [8]
  - Annealing behavior correlated with H diffusion, Ref. [6],[7]
- Review of possible defect structure models and reaction mechanisms, Ref. [9]
- Recent theoretical analysis and proposed mechanisms, Ref. [7],[10]
- Simulation of a-Si:H device performance upon light exposure, Ref. [11]
  - Thinner cells show reduced light-induced performance degradation

Seasonal Effects in a-Si

- Seasonal effects
  - Correlation of a-Si performance with daily mean temperature, Ref. [2][A]
  - Due to partial annealing of defects causing SWE
  - 10-15% relative changes
- Temperature effects in light soaking
  - Stabilized efficiency depends on temperature during exposure, Ref. [12][B]
  - SWE degradation vs. annealing
  - Warm-soak = higher efficiency
- Stabilization of module performance correlated with temperature at installation site, 2008 study
  - Modules installed at higher-temperature locations have better performance, Ref. [13]
  - Similar for single, dual, triple-junction



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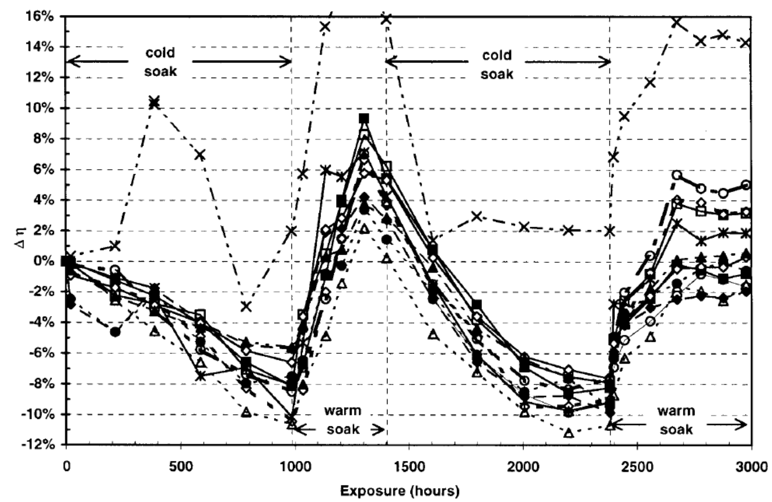
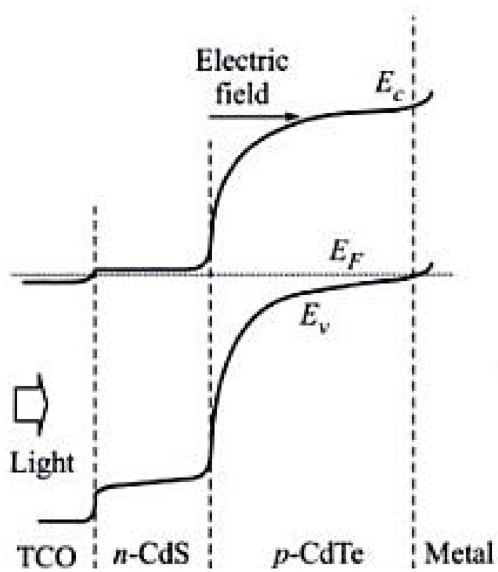


From Ref. B. Cold soak ~ 25 °C; Warm soak ~ 50 °C.

CdTe

CdTe Cell Structure

- CdTe device structure: TCO / n-CdS / p-CdTe / back-contact ([14][A], [15], [16], [17][B])
- Back-contact metallization problematic – requires high work function for ohmic contact
  - Various back-contact metallizations used (see e.g. [18]).
  - A Te-rich interfacial layer is beneficial. Ref. [18], [19]
  - A Cu component is beneficial, although Cu diffusion causes stability issues.



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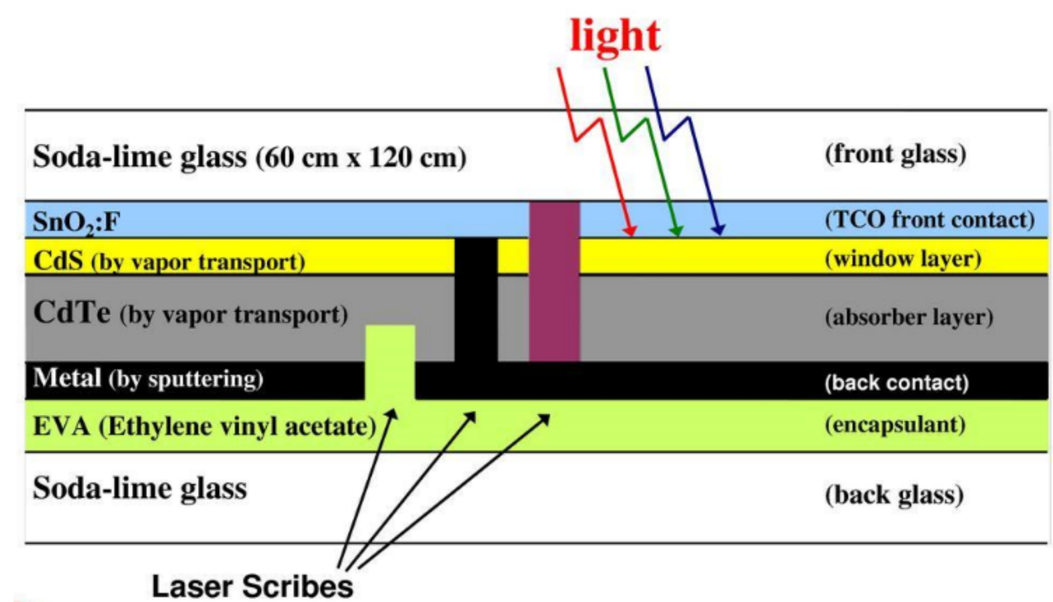
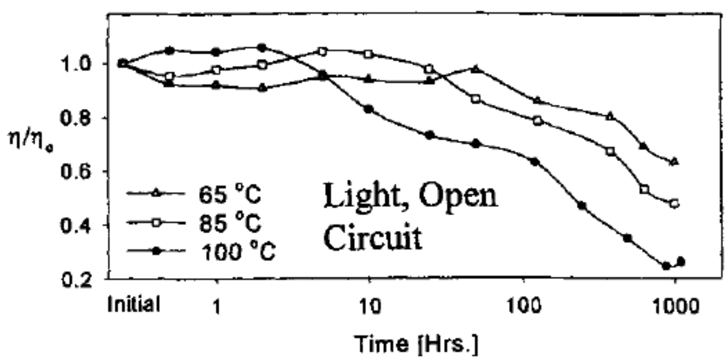


From Ref. B

Extended Duration Light Soaking of CdTe

- Extended duration studies of light soaking reveal need for long-term testing. [20][A]
- Accurate determination of long-term performance required >5000 hours of light soaking per sample.

- High temperature accelerates degradation [21][B]



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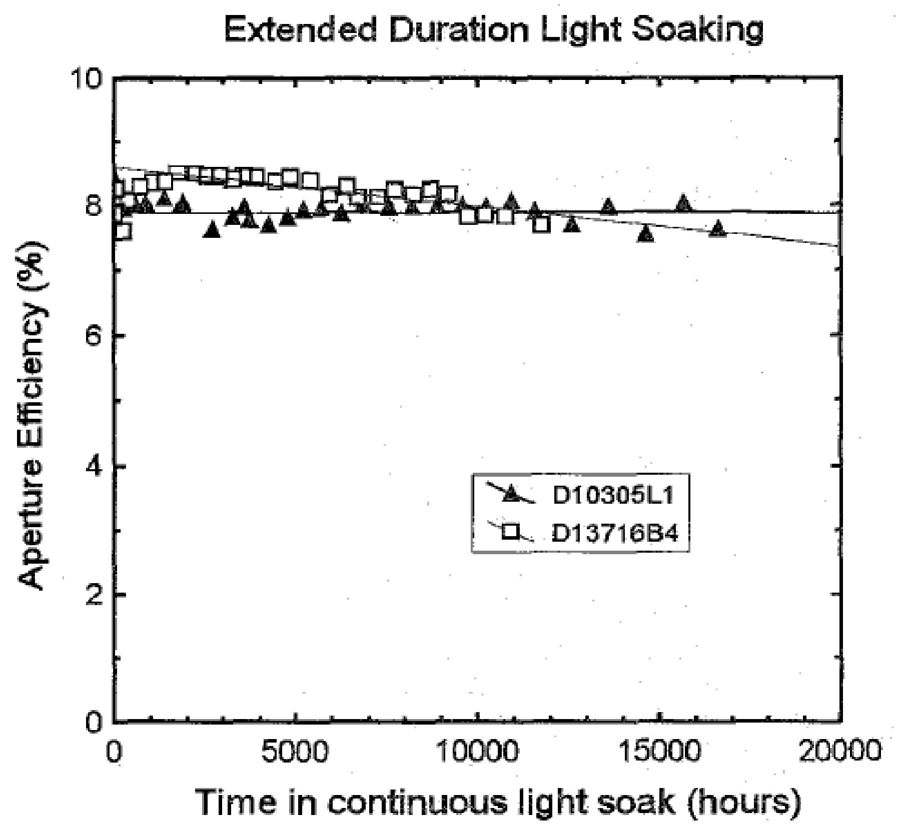
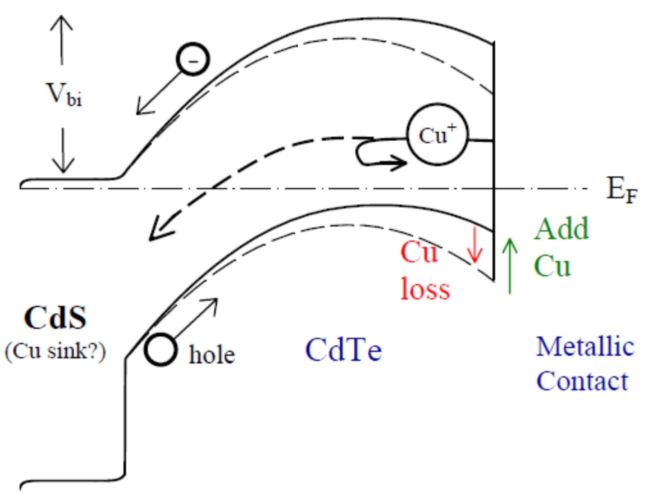


Figure 1. Performance history of two sub-modules fabricated using different recipes. The need for long term testing is apparent.

From Ref. A

Copper Diffusion from Back-Contact in CdTe

- Cu diffusion, Ref. [22][A],[23],[24][B]
  - Back contact in CdTe forms diode of opposite polarity, limiting performance
    - See e.g. modeling in [25]
  - Addition of Cu lowers back-barrier height and improves J-V performance [24]
- Cu loss via diffusion through CdTe (e.g. at high temperature) increases back-barrier height and reduces fill factor
- Light soaking stress leads to efficiency loss



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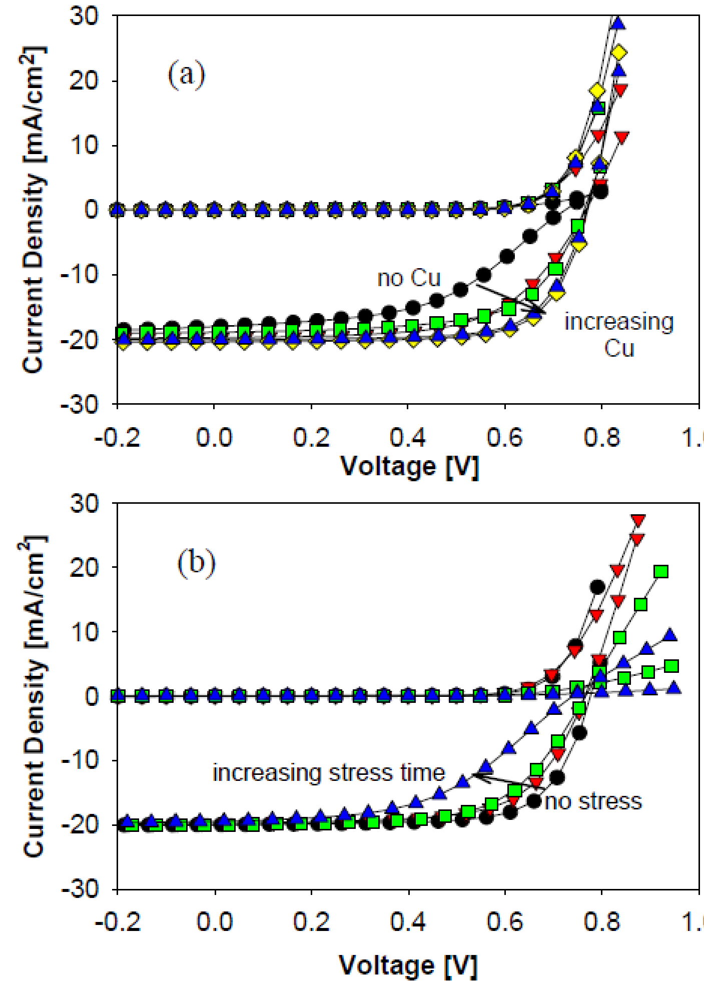
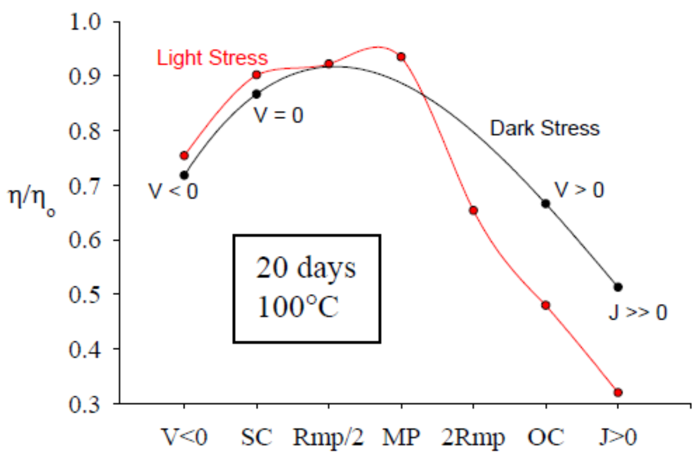


Figure 3. Variations in J-V curves with (a) amount of copper concentration and (b) stress time [from Ref. 5].

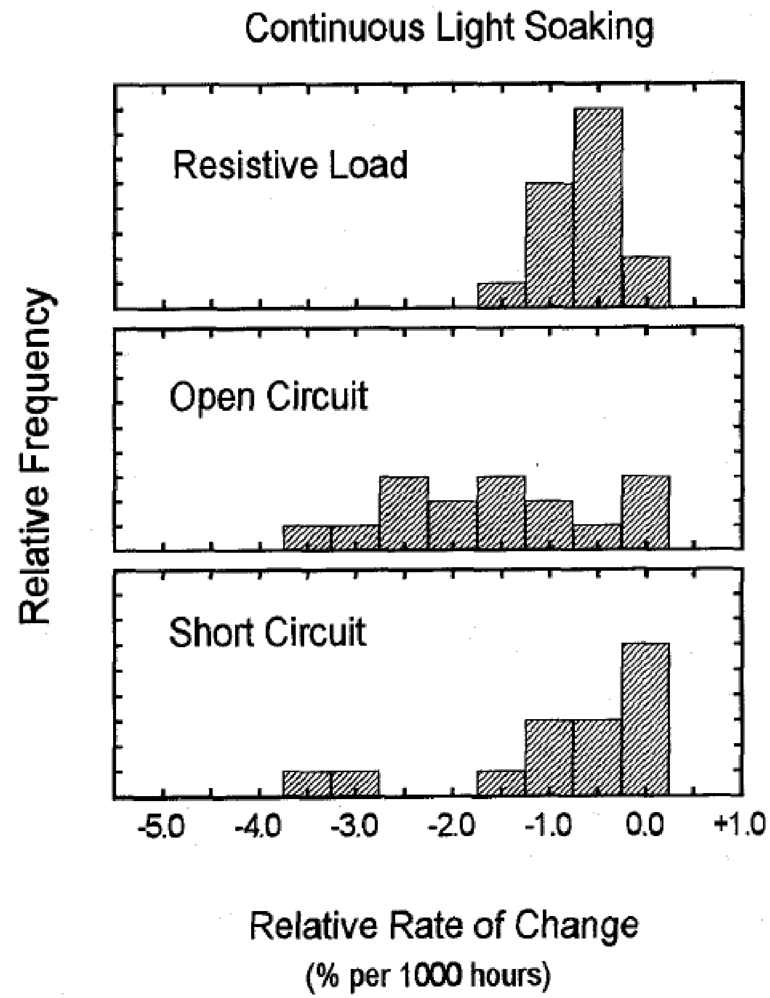
From Ref. A after B

Effect of Bias During Light-Soaking of CdTe

- CdTe degradation during extended light soaking is strongly affected by bias condition Ref. [22][A], [21][B],[20][C]
- Degradation rate increases with increased temperature, Ref. [21]
- Degradation significantly faster at 100C than in the field. Can use high temperature as accelerated test, Ref. [21]



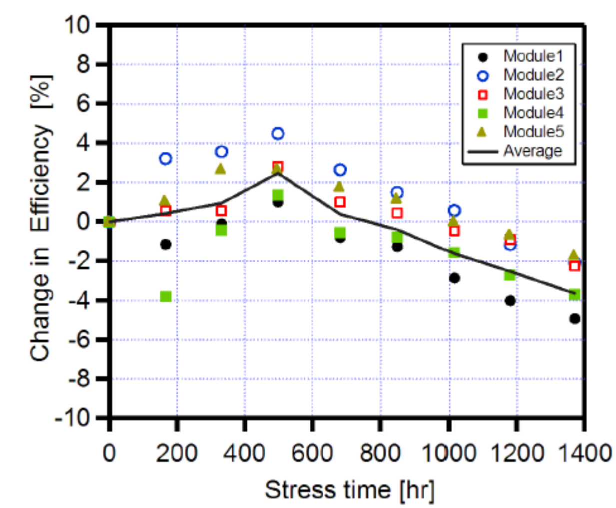
Efficiency drop during extended stress as function of bias condition. From Ref. A after B



From C

Stability in Various CdTe Devices

- Stability of CdTe modules, Ref. [26][A]
    - Light soaking stress yielded initial efficiency improvement, followed by degradation
- Metastable effects in CdTe, Ref [27]
    - Measurements of I-V curves in-situ during extended light soaking of CdTe modules
    - Shifts in Isc, Voc, and FF versus light exposure
    - Voc could move either up or down with exposure, depending on fabrication details
    - I-V parameters depend on module stabilization
- Investigation of CdTe back contacts, Ref [28]
    - Without Cu: initial performance similar to devices with Cu following stress
- Degradation in CdTe with Sb-based back contacts
    - Back contacts based on Sb_2Te_3/Mo yielded stable cells, Ref. [18][B]
    - Sb_2Te_3-based back contacts, Ref. [29]
        - Outdoor testing of CdTe for 1.5 years
        - Degraded ~5% in Voc and 8-10% in FF



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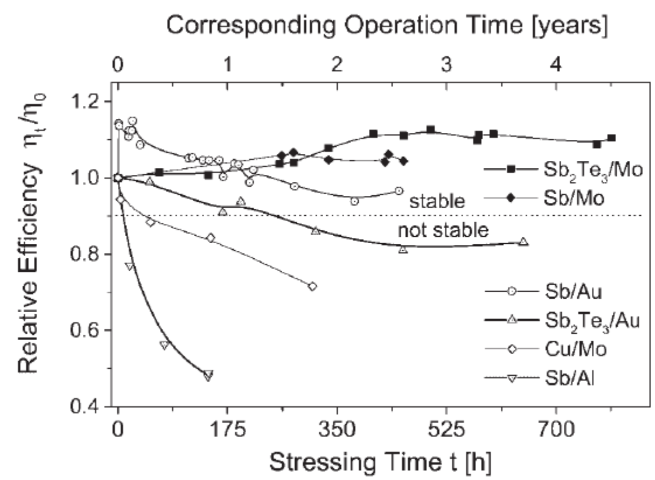
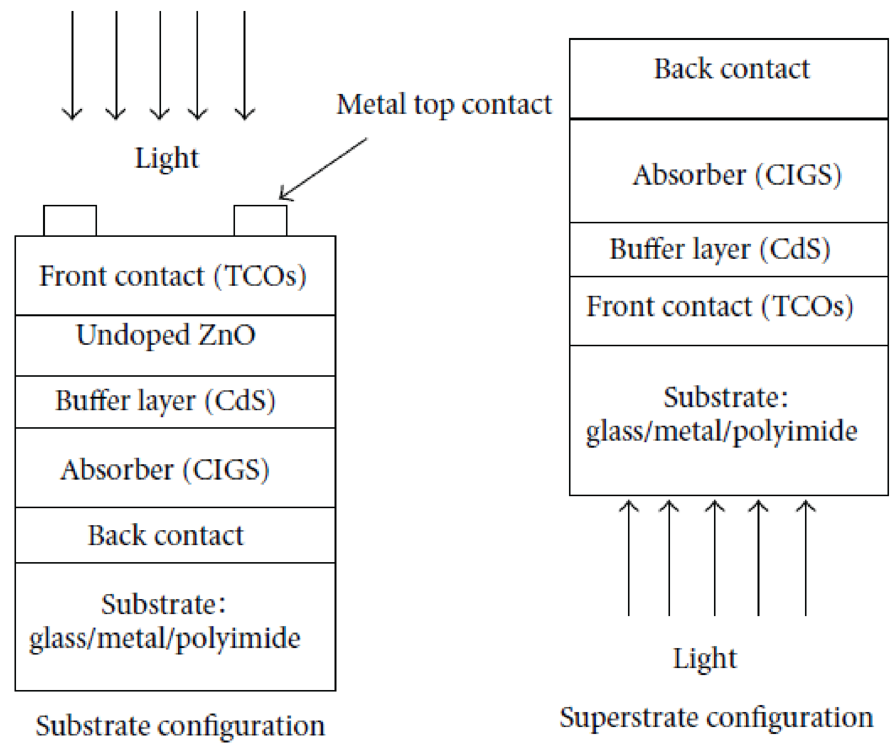


Stability vs. back contact materials. From Ref. B

CIGS

CIGS Device Structure

- CIGS = Copper Indium Gallium Selenide = $Cu(In,Ga)Se_2$
- Device structure, Ref. [30][A],[31], [18]
- Typically uses CdS buffer layer
- Typically formed in substrate configuration
    - If superstrate, undesirable CdS diffusion during CIGS deposition
- Desire for structures without CdS
    - Various approaches



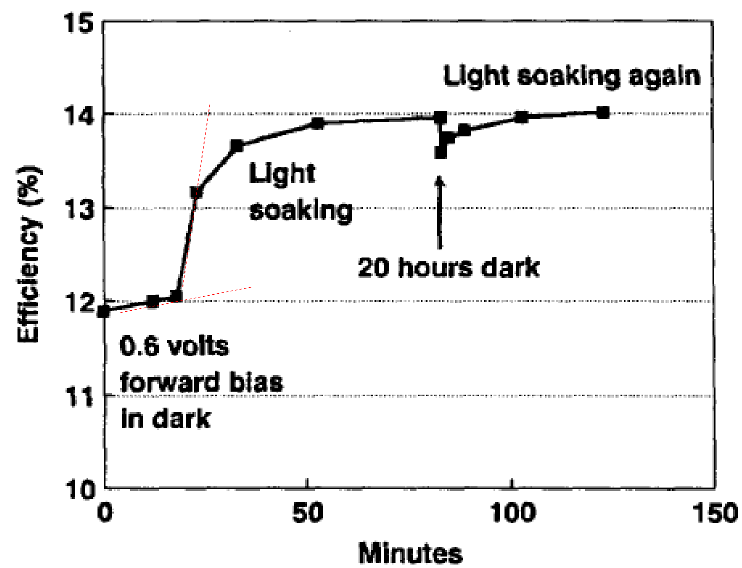
From Ref. A

CIGS Light Soaking Effects

- Reversible metastability of photoconductivity in CIGS films, Ref [32]
  - Annealing at 80 °C leads to decrease of dark conductivity by ~2x at room temperature
  - By exposure to light, the initial state can be re-established

- Voc of CIGS cells shifts reversibly with light exposure or bias, Ref [33]
  - CIGS Voc rises upon light exposure or forward bias in dark, with corresponding rise in efficiency of ~5%
  - Time scale ranges from minutes to hours; faster at higher temperature

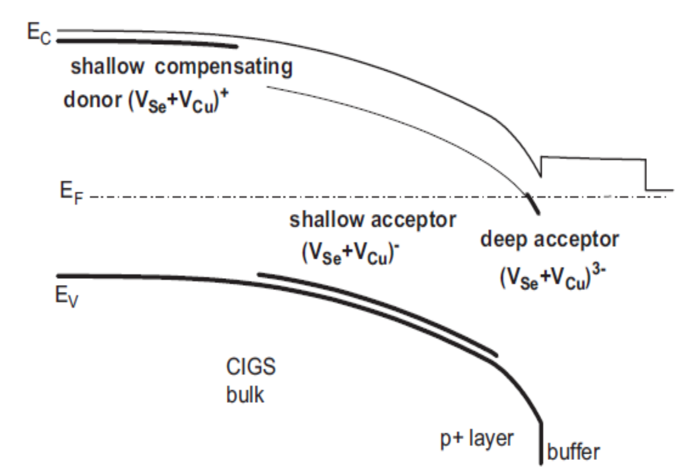
- Effects of sweep rate and voltage bias on CIS cells, Ref [34][A]
  - Light soaking produced 7-15% improvement in cell efficiency
  - Light soaking effect more pronounced and longer lived than effect of forward bias



From Ref. A

CIGS Metastability Mechanisms

- Three effects in CIGS metastabilities, Ref [35],[36]
  - Light soaking with white light may produce overall beneficial effect due to balance of beneficial and detrimental effects [36]
  - Red light: increase in Voc, due to increase in carriers in absorber
    - Similar effect from forward bias
  - Blue light: interface effect
  - Reverse bias: interface effect
- Proposed mechanisms, Ref. [36]
  - Metastable defects that trap carriers
  - Reversible migration of Cu
- Amphoteric Se-Cu divacancy (V_{Se}-V_{Cu}) complex
  - First principles calculations, Ref. [36]
    - V_{Se}-V_{Cu} complex can act as amphoteric (donor or acceptor) defect
    - Defect state converted by light absorption
    - Explains observed effects of red light, blue light, and reverse bias
  - Experimental support
    - Refs. [37], [38], [39], [40][A]



From Ref. A

Light Soaking in CIGS with Alternative Buffer Layers

- Light soaking effects vary greatly depending on the device structure and especially the buffer layer composition.

- Strong light soaking effect observed:
  - Superstrate CGS/CIGS cells grown with ZnO buffer instead of CdS, Refs. [41], [42]
  - ZnO/CIGS cells without CdS, Ref. [43]
  - $Zn_{1-x}Mg_xO$ buffer layers without CdS, Ref. [44]

- Minimal light soaking effect observed:
  - CIGS with ZIS (Zn-Indium-Se) buffer layer (alternative to CdS), Ref. [45]

Thin-Film Pre-Conditioning

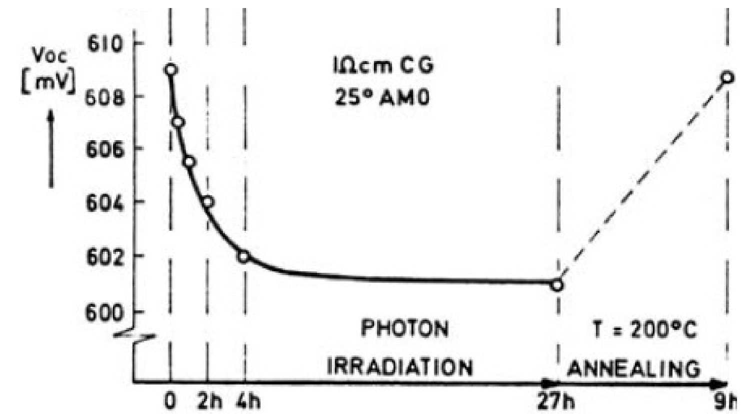
Thin-Film Pre-Conditioning

- Due to metastability phenomena, preconditioning is essential for accurate power output determination of thin film PV modules.
- However, due to the complexity of the phenomena and variability between different module technologies, reliable preconditioning methods are difficult to establish.
- Current standard for stabilization in thin-film PV modules is IEC 61646
  - <2% change after successive 43 kW/m^2 exposure periods
  - Designed primarily for a-Si where dominant degradation is via Staebler-Wronski effect
- Questions:
  - Can modules be stabilized via dark soaking (at bias? at temp?), without light soaking?
  - What are optimal temperatures and durations for stabilization?
- Recent CdTe preconditioning examples:
  - CdTe efficiency found to initially improve, then degrade, with light exposure, Ref. [26]
  - CdTe efficiency measurements depend strongly on pre-conditioning conditions, with various conditions yielding higher or lower efficiency results, Ref. [46]
- Recent NREL studies on pre-conditioning techniques for CdTe & CIGS, Refs. [47], [48], [49]
  - Comparing effects of light soaking and dark-bias-soaking
    - Some modules stabilized equally in light vs dark-bias, while others do not
  - Comparing indoor to outdoor stabilization

Crystalline Si

Light-Induced Degradation (LID) in Crystalline Silicon

- Boron-doped crystalline Silicon solar cell material includes:
  - Czochralski-grown monocrystalline silicon (Cz-Si)
  - Cast multicrystalline silicon (mc-Si)
- LID in Cz-Si solar cells, Ref. [50][A],[51],[52],[53]
  - ~4% power output degradation in B-doped Cz-Si cells during first 5 hours of light soaking
  - Recovers upon anneal or dark storage [51]
  - Due to activation of metastable boron-oxygen defect which lowers carrier lifetime
  - Greatly reduced using either Ga-doped Cz-Si or low oxygen content B-Cz-Si, [52]
- IEC 61215 preconditioning
  - Qualification for c-Si modules requires 5 hours of preconditioning at 1000 W/m^2 prior to power output measurement
- Statistical review of LID in different monocrystalline Cz-Si and mc-Si modules, Ref. [54]
- LID may also be present in upgraded metallurgical grade or low-cost silicon, Refs. [55],[56]



Observation of LID in B-doped Cz-Si solar cells.
From Ref. A

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