LIGHT SOAKING EFFECTS ON PHOTOVOLTAIC MODULES: OVERVIEW AND LITERATURE REVIEW

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ABSTRACT

Device performance under extended duration illumination is an essential characterization step for any PV technology, because light exposure can produce a variety of effects which influence the determination of both initial and long-term stabilized device performance. We present an overview of PV light soaking behavior based on a literature review of light soaking effects on commercial PV module technologies, including a-Si/μc-Si, CdTe, CIS/CIGS, and c-Si. We address the physical mechanisms of light-induced changes in each PV technology, short- and long-term light-induced effects, and current literature knowledge on PV module preconditioning for accurate power output determination. We highlight common themes and identify desirable attributes of equipment for PV module light soaking characterization and test.

INTRODUCTION

Nearly all PV technologies exhibit changes in device performance under extended duration illumination, or “light soaking,” although the magnitude of these changes is much greater for some technologies than for others. Such changes include reversible metastable phenomena, in which the PV device performance can alternate between different states depending on history of illumination, electrical bias, and temperature, as well as long-term effects in which the device performance is fundamentally altered.

LIGHT SOAKING IN MAJOR DEVICE TYPES

Amorphous Silicon

Amorphous silicon (a-Si) is one of the earliest thin film PV technologies and exhibits a well-known light-induced degradation effect, in which efficiencies degrade by ~10-30% in the first several hundred hours of light soaking [1]. The degradation is due to the well-known Staebler-Wronski effect (SWE), first observed as a reduction in the dark conductivity and photoconductivity of a-Si:H after light exposure, wherein the degradation is reversible by annealing at high temperatures. The SWE occurs due to the recombination-induced breaking of weak Si-Si bonds by optically excited carriers after thermalization, producing defect centers that lower carrier lifetime [2]. Device recovery occurs upon annealing as defects are healed.

The degradation effect requires light exposure; defects introduced by alternate methods such as current injection or keV bombardment produce different results [2,3,4]. The effect can be accelerated by high-intensity pulsed light at low temperatures [3]. The exact microscopic mechanism of the SWE is not fully understood. Several authors have provided reviews of possible defect structure models and reaction mechanisms [4,5,6].

Experiments have demonstrated that the stabilized efficiency of a-Si modules depends on their temperature during light exposure [7]. Higher temperature alters the balance between the detrimental effects of light exposure and the beneficial effects of annealing, with warm light soaking leading to higher efficiency. This explains the well-known seasonal effect in fielded a-Si PV modules, in which performance is positively correlated with daily mean temperature [1], resulting in 10-15% relative seasonal changes in performance. Similarly, a-Si modules rotated between multiple sites exhibited highest performance when installed in warmer locations [8].

Device structure may be an important variable in light-induced degradation of a-Si PV. Simulation and experiment demonstrate that cells with thinner intrinsic layers show reduced light-induced performance degradation, due to reduced recombination of charge carriers [9].

Light-induced degradation effects are typically less severe in multi-junction amorphous silicon PV as compared to single-junction devices. Furthermore, the degree of light-induced degradation is significantly reduced in devices employing mixed phases of amorphous and micro- or nano-crystalline silicon. Several reports show that the degree of degradation is proportional to the amorphous content [10,11]; other studies show that nanocrystalline silicon devices with high amorphous content may still have very low levels of light-induced degradation when fabrication methods result in phases with many small grains and long-range order [12,13]. This research has shown promising results with high-efficiency stable cells having light-induced degradation as low as 2%.

CdTe

CdTe PV devices typically contain an n-type CdS buffer layer followed by a p-type CdTe absorber layer and a back-contact metallization layer for current collection [1,14,15]. The back-contact metallization scheme is problematic due to the requirement of a high work function for ohmic contact to CdTe, and various back-contact metallizations have been used. (See e.g. [16].) A Te-rich interfacial layer is beneficial [16,17] and often a Cu component is incorporated, although Cu diffusion causes stability issues.

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CdTe PV devices often exhibit an initial performance shift upon light exposure. In an early observation [18] the open-circuit voltages of CdTe cells from a variety of sources were found to improve by ~4% with either light exposure or forward bias in the dark. The effect was found to be reversible upon unbiased dark storage, and to have time constants on the order of hours for both the initial shift and subsequent relaxation. The shift has been ascribed to the existence of trap states in the absorber junction which depopulate when the cell is forward biased [18]. The result is a requirement for preconditioning cells before performing efficiency measurements.

Experiments on commercial CdTe PV modules have shown transient effects on module performance with initial light soaking over periods of even hundreds of hours. In [19] the efficiency of one group of modules was found to improve by ~6-8% with ~1000 hours of exposure – with the improvement at least somewhat reversible in dark storage – while the efficiency of another group of modules degraded by 7-15% with the same amount of light exposure. The results illustrate differences due to device fabrication processing details.

Measured device performance can vary greatly depending on preconditioning procedures, as shown, for example, in [20].

With long-term light exposure CdTe devices typically exhibit performance degradation due to detrimental permanent changes in the device. For example, devices in [21] showed initial efficiency improvement under light soaking followed by long-term degradation. Extended duration studies of light soaking in CdTe modules revealed the need for long-term testing to quantify such degradation. The authors of [22] tracked device performance over thousands of hours and found that accurate determination of long-term performance typically required >5000 hours of light soaking. However, observed degradation could also be accelerated by light soaking exposure at higher temperatures [23].

The diffusion of Cu ions away from the back contact metallization in CdTe devices can explain many of the observed long-term light soaking effects [24,25,26]. The back contact in CdTe forms a diode junction of opposite polarity to the main junction, limiting performance [27]. Addition of Cu lowers the back-barrier height and improves I-V performance [26]. However, at high temperature, Cu is lost from the back barrier via diffusion through CdTe, increasing the back-barrier height and reducing fill factor. Light soaking stress therefore leads to efficiency loss. The degradation rate increases with increased temperature and is significantly faster at 85-100 °C than at temperatures observed during normal operation [23]. Thus, accelerated testing can be performed by using a high-temperature light soak.

Furthermore, CdTe degradation during extended light soaking is strongly affected by the electrical bias condition [22,23,24], with open-circuited devices showing greater degradation than those operating at max power. This is believed to be due at least in part to the retardation of Cu ion migration by internal electric fields when the devices operate near max power.

Long-term stability of the back contacts in a given CdTe device also depends strongly on the specifics of the device fabrication. The behavior and ultimate stability under light soak varies especially with the choice of back contact metallization [28].

In addition to modification of the back contact due to diffusion under light and bias stress, other mechanisms may lead to long-term degradation. For example, the authors of [29] found evidence for increases in series resistance of front contact transparent conducting oxide layers in samples cut from field-tested CdTe modules, which employed Sb-based back contacts, after about 1.5 years of outdoor exposure.

CIS/CIGS

Devices in the copper indium gallium selenide family ($Cu(In,Ga)Se_2$ or CIS/CIGS) are typically formed in a substrate configuration with deposition of a CIS or CIGS absorber layer followed by deposition of a CdS buffer layer [1].

CIS/CIGS devices exhibit a well known beneficial reversible metastability under light soaking. For example, the authors of [30] found that light exposure for periods on the order of hours yielded an increase in the photoconductivity of CIGS films, which was reversed upon annealing at 80 °C in the dark. The open-circuit voltages of both CIS [31] and CIGS [32] improve by several percent with illumination over periods ranging from minutes to hours with cells at forward bias conditions, with the magnitude of improvement depending on device details. These effects are driven at least in part by electrical bias, rather than light absorption *per se*. For example, in [31] holding cells at short-circuit during illumination eliminated the increase in open-circuit voltage, while subjecting the cells to forward bias in the dark shortened the time constant for subsequent open-circuit voltage increase.

The metastability has a significant beneficial effect on device performance. In [18] CIS cells exhibited a reversible increase in efficiency of ~5% with either light exposure or forward bias. The conditioning time required to observe the improvement was shorter at higher temperature. In [33] light soaking produced ~7-15% improvement in efficiency in CIS cells. Notably, the light soaking effect was believed to be more pronounced and longer-lived than the effect of forward bias alone.

More detailed investigations reveal a wavelength dependence to the illumination-driven metastabilities. “Red” light, absorbed primarily in the CIS or CIGS absorber layer, produces different effects than “blue” light, which may be absorbed in the CdS buffer layer [34,35], and separate effects are distinguished for wavelengths absorbed near the interfaces versus in the bulk [36]. Light soaking with white light may produce an overall beneficial effect due to a balance of beneficial and detrimental effects [35].

Numerous explanations have been proposed to explain the origin of CIGS metastabilities, including the creation and/or neutralization of metastable defects and reversible migration of ions under bias during device operation. Recent calculations [35] and experiments [37,38,39] suggest that the various metastable effects have a common origin in an amphoteric Se-Cu divacancy complex which is converted between donor and acceptor states by light absorption.

Light soaking effects in CIGS devices vary greatly depending on the device structure and especially the buffer layer composition. Attempts to replace the CdS buffer layer with an alternate material (to eliminate Cd and reduce environmental impact) have yielded devices with both strong [40,41,42,43] and weak [44] light soaking effects.

CIGS modules that have experienced dark storage – especially at elevated temperatures – should be light soaked prior to efficiency measurement. Efficiency reductions of up to 20% in CIGS devices following damp-heat tests (such as performed in module qualification procedures, e.g. IEC 61646) have been shown to be largely reversed by light soaking [45].

For long-term light exposure, CIS/CIGS devices appear to be very stable. Although moisture ingress can cause significant degradation modes, well encapsulated modules show very little degradation in multi-year outdoor field tests [46,47], indicating the inherent stability of the devices to long-term light exposure. The devices are also known to be particularly tolerant to defects induced by radiation or impurities; the fast diffusion of Cu ions within the material may play a role in improving stability by healing defects [48].

However, under certain conditions light exposure may indeed result in degradation. The authors of [49,50] studied the stability of CIS modules under repeated light/dark irradiation cycles, and found that open-circuited modules showed initial performance improvement followed by degradation after about 8 daily cycles, while short-circuited modules showed no such degradation. In [51] CIGS modules tested for one year outdoors showed significant degradation for samples with cell mismatch versus little degradation for samples with good matching. These examples illustrate the influence of electrical conditions on device stability under extended light exposure.

Crystalline Si

Discussion of light-induced metastabilities typically focuses on thin film materials, but PV devices using boron-doped Czochralski-grown monocrystalline silicon (Cz-Si) also exhibit an initial light-induced degradation effect, corresponding to ~4% power output degradation during the first ~5 hours of light soaking [52,53]. The effect is reversed upon anneal or dark storage. It is due to the light-induced activation of a metastable boron-oxygen defect which lowers carrier lifetime. The effect can be greatly reduced using either Ga-doped Cz-Si or low oxygen content B-Cz-Si [52]. The effect is not present in cast multi-crystalline silicon (mc-Si) devices, which have lower oxygen impurity, although the efficiencies of these devices are somewhat lower and therefore similar to those of Cz-Si following light soaking. The IEC 61215 qualification procedure for crystalline silicon PV modules requires a 5-hour light soak prior to testing, which ensures that Cz-Si modules are stabilized. Ref. [54] surveyed light-induced degradation in different monocrystalline Cz-Si and mc-Si modules. The metastability may also be present in upgraded metallurgical grade or low-cost silicon [55,56].

THIN-FILM PRE-CONDITIONING

Metastability and light-induced degradation phenomena associated with thin film PV modules make preconditioning methods essential for accurate power output determination of these technologies. However, the complexity of the phenomena and variability between different module technologies make universal preconditioning methods difficult to establish.

The current standard for stabilization in thin-film PV modules is given in IEC 61646, which requires <2% change in module power output after successive 43 kW-hr/m^2 exposure periods at ~1000 W/m^2. However, this procedure is designed primarily for a-Si where the dominant degradation is via the Staebler-Wronski effect, and is likely not optimal for CdTe or CIGS devices [57,58].

Several questions arise. How should module stabilization be defined? Can modules be stabilized via dark soaking alone – without light soaking – for example at electrical bias and elevated temperature? What are optimal temperatures and durations for stabilization, with or without light?

Recent NREL studies address these questions, focusing on optimal pre-conditioning techniques for CdTe and CIGS. Several projects compared the effects of light soaking versus dark-bias-soaking [57,58,59,60]. Results varied, as some modules stabilized equally in light vs. dark-bias while others did not. An important goal is to identify indoor laboratory techniques for module stabilization that are validated by actual outdoor performance. Such studies are underway [60].

Adherence to a specified program of thin film PV preconditioning is particularly important for comparison between test laboratories. Recent round-robin tests between seven European labs found thin film module power ratings varying +/-6%, largely due to differences in preconditioning procedures [61,62].

SUMMARY

Although there are many details, the effects of light exposure on the main commercial PV technologies can be summarized as follows. For a-Si PV, light exposure leads to degradation of module power output, while high temperatures lead to improvement. Newer technologies incorporating nanocyrstalline silicon may exhibit reduced light-induced degradation. For both CdTe and CIS/CIGS, dark exposure leads to states with lower efficiency which can be reversed by light exposure. For CdTe in particular, operating modules under load during light exposure is important to counteract potential degradation mechanisms. Even some crystalline silicon PV technologies exhibit metastabilities requiring stabilization by light exposure.

DISCUSSION

Reliable methods for accurate power output determination of PV modules are essential not only for evaluating and rating module performance, but also for routine performance monitoring in manufacturing environments to assess the effects of process variations and to maintain quality control. Ideally, a universal procedure could be defined that would reproducibly stabilize all thin-film PV module technologies. In reality the optimal stabilization procedure may vary from one module technology to another, and even depend on processing details.

The sensitivity of light soaking effects to the specific details of device fabrication suggests that light soaking characterization may be an important tool in a manufacturing environment. A review of the associated phenomena suggests some desirable characteristics of light soaking test equipment. Because of the significant role that electrical bias conditions play in module stabilization, light soaking equipment preferably contains integrated current-voltage measurement capability for applying electrical load/bias to the devices under test and/or tracking device performance *in-situ*. In addition, such equipment should offer temperature control over an extended range that includes not only typical operating temperatures but also higher and lower temperatures that may accelerate or retard degradation mechanisms.

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