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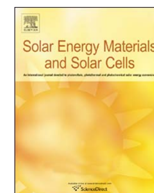

Increasing the efficiency of silicon heterojunction solar cells and modules by light soaking

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A B S T R A C T

Silicon heterojunction solar cells use crystalline silicon (*c*-Si) wafers as optical absorbers and employ bilayers of doped/intrinsic hydrogenated amorphous silicon (*a*-Si:H) to form passivating contacts. Recently, we demonstrated that such solar cells increase their operating voltages and thus their conversion efficiencies during light exposure. We found that this performance increase is due to improved passivation of the *a*-Si:H/*c*-Si interface and is induced by injected charge carriers (either by light soaking or forward-voltage biasing of the device). Here, we discuss this counterintuitive behavior and establish that: (i) the performance increase is observed in solar cells as well as modules; (ii) this phenomenon requires the presence of *doped a*-Si:H films, but is independent from whether light is incident from the *a*-Si:H(*p*) or the *a*-Si:H(*n*) side; (iii) UV and blue photons do not play a role in this effect; (iv) the performance increase can be observed under illumination intensities as low as 20 W m^{-1} (0.02-sun) and appears to be almost identical in strength when under 1-sun (1000 W m^{-1}); (v) the underlying physical mechanism likely differs from annealing-induced surface passivation.

1. Introduction

Silicon wafers with excellent bulk electronic properties and layers providing high-quality surface passivation are now widely available for realizing solar cells. Consequently, carrier recombination at the electrical contacts is now the major electronic loss in silicon solar cells, because direct metal/silicon interfaces feature a high density of recombination-active localized states. This high surface-state density increases the recombination rate of photo-generated or injected carriers at the interface. Such recombination can be mitigated by introducing a high surface doping which screens the metal/silicon contacts from minority carriers. The so-called passivating-contact technologies aim at minimizing these losses by drastically reducing the surface-state density of silicon near the contact. To this end, films made from intrinsic hydrogenated amorphous silicon (*a*-Si:H) are a particularly attractive choice for solar cells because they are at the same time conductive (if thin enough) and they provide excellent passivation of crystalline silicon (*c*-Si) surfaces by removing the *c*-Si surface states, even when they are only a few nanometers thick [1–5]. Moreover, such films can be doped, increasing further their functionality [6]. When effectively doped, *a*-Si:H films usually do not exhibit good passivation, but when they overlay thin intrinsic *a*-Si:H layers, they can efficiently collect either electrons or holes (in case of *n*-type and *p*-type overlayers, respectively), while maintaining very high internal voltages [7–10]. Solar cells that feature such doped/intrinsic *a*-Si:H contacts are usually referred to as silicon heterojunction (SHJ) solar cells, which is a technology pioneered by Panasonic, Japan (then Sanyo) [11]. Kaneka, Japan recently demonstrated the effectiveness of SHJ by setting a new single-junction silicon solar cell efficiency record at 26.6% using doped/intrinsic *a*-Si:H contacts in a fully back-contacted layout [12]. In their most simple implementation, SHJ solar cells have electron- and hole-collecting contacts on the opposite sides of the wafer. The best reported efficiency for this implementation is 25.1%, also established by the same company [13].

Long-term stability under actual operating conditions is an important criterion for any solar technology. In this context, conflicting

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data on the stability of SHJ-based photovoltaics have been reported. For example, Jordan *et al.* reported that SHJ modules degrade at a faster rate than do other *c*-Si based modules (1% versus 0.5–0.8% annual degradation, respectively) [14]. However, Sharma et al. found an increase in V_{oc} of a SHJ module after 28 months in the field [15]. Recently, we demonstrated that light soaking (LS) of SHJ solar cells increases their open circuit voltage (V_{oc}) and fill factor (*FF*), leading to a gain in absolute conversion efficiency of up to 0.3% [16]. In particular, we found that the electronic passivation of *c*-Si surfaces coated with *p*- or *n*-type doped *a*-Si:H films or with bilayers of *p*- or *n*-type/intrinsic *a*-Si:H under prolonged LS was improved. Mahtani *et al*. reported a similar trend for *p*-type/intrinsic *a*-Si:H bilayers [17]. Based on these results, the loss in SHJ module performance reported by Jordan et al. may not have been the result of light-induced cell degradation, but arguably was caused by other factors, possibly linked to early-generation technology. Despite its direct beneficial impact on power generation of SHJ-based photovoltaics, light-induced performance improvement is not yet well understood. However, fundamental insight into the underlying physics of light-induced performance may lead to further device sophistication, increasing performance. Performance improvement under LS is actually unusual, as most silicon-based technologies are either stable or exhibit degradation under LS conditions. A classic example of light-induced degradation (LID) is the so-called Staebler–Wronski effect (SWE), which degrades the performance of thin-film *a*-Si:H solar cells [18–21]. Another example of LID is associated with *p*-type, *c*-Si-based solar cells, caused by the formation of a recombination-active boron-oxygen complex in the bulk of the wafer [22,23]. In contrast, V_{oc} improvement induced by light soaking is well known in both major thin-film technologies CdTe [24] and CIGS [25]. In addition, V_{oc} improvement induced by light soaking has been reported for *a*-Si:H devices by a variety of institutes and explained [26].

Perhaps counterintuitively, it is possible that light-induced performance improvement in SHJ cells is related to SWE. In this case, remarkable *FF* improvement is also observed as well as V_{oc} improvement. Previously, we found that the passivation of *intrinsic a*-Si:H/*c*-Si interfaces decays upon long-term LS, following identical kinetics (in the form of power laws) to that for LID in bulk *a*-Si:H solar cells [27]. The underlying kinetics of *doped a*-Si:H/*c*-Si interfaces is also similar to that of SWE, as indicated by power laws [16]. Recently, Melskens *et al.* discussed the degradation mechanism of SWE, but its kinetics can impossibly be described by single time scaling ($\sim t^{\beta}$), which means that some parts remain unexplained [28]. The effect of doping, and more generally the position of the Fermi-level, in bulk *a*-Si:H is described in defect-pool models [29–35], but the effect of LS on such doped layers on a *c*-Si absorber remains unclear, doubtlessly because thin-film *a*-Si:H devices are exclusively fabricated in a so-called *p-i-n* configuration, with the optically active absorber consisting of intrinsic *a*-Si:H [36], where the Fermi-level never deviates much from midgap.

Similarities and differences between earlier findings around LS raise several important questions about the precise impact of the *a*-Si:H/*c*-Si heterointerface. For example, in *a*-Si:H/nanocrystaline (*nc*)-Si double junction solar cells, LID is mainly observed in the top cell, because the *a*-Si:H top cell absorb most of the high-energy photons [37]. Additionally, low-energy photons just above the bandgap of *a*-Si:H still lead to a degradation of the top cell. How do the high-energy photons play a role in the LS effect? Moreover, the degree of SWE in bulk *a*-Si:H is related to the carrier recombination rate which is related to the generation rate G_e, and thus to the applied light intensity [38]. Does the LS effect similarly depend on light intensity? Finally, post-deposition passivation improvement by low-temperature annealing (< 200 °C) is a well-known phenomenon in SHJ solar cells [39]. To what extent does its underlying mechanism hold relevance to the light-induced improvement of SHJ cells? Related to this, will post-annealing after LS improve SHJ solar cells? Here, we seek answers to these questions by describing the LS phenomenon in SHJ solar cells in detail.

2. Experimental details

To evaluate current density–voltage (*J*–*V*) characteristics under LS, we fabricated four types of SHJ solar cells and a precursor. Two of the four types were 3-busbar solar cells, one with front-emitter (sample set A) and the other with rear-emitter (sample set B). Both 3-busbar types were 243.4 cm^2 in size. The other two of the four types were busbarless solar cells, one with rear-emitter (sample set C) and the other with front-emitter (sample set D). Sample set C were 243.4 cm^2 in size. Sample set D were a 4 cm^2 device with contact electrodes for 4-point probes method to evaluate *J*–*V* characteristics under LS at selected wavelengths. We also fabricated solar cell precursors, missing transparent conductive oxide (TCO) layers and electrodes (sample set E), for evaluating minority carrier lifetimes under LS with different light intensities. We used *n*-type Czochralski Si(100) wafers (with a resistivity of 2.9 Ω cm) as absorbers in all four SHJ solar cell designs and a precursor of finished cells. These wafers were textured in an alkaline solution and wet-chemically cleaned. The textured wafers (with a thickness of 180 µm) were then dipped in 5% hydrogen fluoride solution just before plasma-enhanced chemical vapor deposition (PECVD). The intrinsic (*i*) and doped (*n* and *p*) *a*-Si:H layers were deposited on both wafer surfaces at 200 °C using mixtures of SiH_4, PH_3, $B(CH_3)_3$, and H_2 in a PECVD tool operated at 13.56 MHz. Schematics of the fabricated cells and precursors are shown in Fig. 1. Our analysis focuses on the asymmetric *i-p*/*i-n* solar cell precursor; we used 6-nm-thick *i* layers for finished cell structures and test structures. The *n* and *p* layers of the finished cell structures were 3-nm thick and these layers of the test structures were 6-nm thick (see Fig. 1). Thicknesses for each *a*-Si:H layer were measured on textured surfaces and calculated from the angle of the texture as visualized by a cross-sectional transmission electron microscope. On the finished cells, indium tin oxide (ITO) films were sputter-deposited as TCO layers on both sides of the wafer, which were then capped with a silver reflector, which was also sputter-deposited, at the rear. Front electrodes (fingers and busbars) were screen-printed from a low-temperature silver paste on the front ITO layer. Finally, the cells were cured at 200 °C for 30 min.

Before LS, pre-annealing was conducted at 200 °C in air under dark conditions. LS was then carried out in a commercial system (Sunirad A-65, Solaronix) under Air Mass 1.5 global (AM 1.5G) illumination (CLASS A, International Electrotechnical Commission (IEC) 60904-9/American Society for Testing and Materials (ASTM) E927-05). The substrate temperature was maintained during LS at 32 ± 2 °C by a water-cooling system, to eliminate a possible temperature induced improvement [40]. To track electronic changes at the *a*-Si:H/*c*-Si heterointerface, excess carrier lifetimes, τ_{eff}, of the wafers were measured with the transient photoconductance technique (WCT-120, Sinton Instruments), which complied with Semiconductor Equipment and Materials International (SEMI) standard PV-13 [41]. The stage temperature during the τ_{eff} measurements was 24 ± 1 °C. The finished SHJ cells were characterized by current–voltage measurements on a 1-sun solar simulator under 1000 W m^{-2} AM 1.5G illumination at 25 ± 0.1 °C by a water-cooling system. To estimate the measurement error, we carried out the cross-check measurements between our site and Japan Electrical Safety and Environment Technology Laboratories (JET) using SHJ solar cells (sample set B, five cells). Consequently, the measurement error was expected to be less than ± 0.1% absolute to cell efficiencies. The external quantum efficiency (EQE) was measured with a spectral response measurement system (CEP-25RR, Bunkokeiki).

3. Results and discusion

Fig. 2 illustrates changes in the conversion efficiency (η) of finished SHJ solar cells using LS under open-circuit conditions with two different light incident directions, one from the *a*-Si:H(*p*) side, the other from the a-Si:H(*n*) side (sample set A and B, respectively, see also Fig. 1). In this graph, $t_{1\text{-}sun}$ is the 1-sun LS time. The averaged initial

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