Substrate versus superstrate configuration for stable thin film silicon solar cells

Ka-Hyun Kim [a,b,c,*], Samir Kasouit [b], Erik V. Johnson [c], Pere Roca i Cabarrocas [c]

[a] Korea Institute of Energy Research—KIER-UNIST Advanced Center for Energy, Ulsan, South Korea
[b] TOTAL S.A., Gas & Power—R&D Division, Courbevoie, France
[c] Laboratoire de Physique des Interfaces et des Couches Minces (UMR7647 CNRS), Ecole Polytechnique, Palaiseau, France

ARTICLE INFO

ABSTRACT

We report on the light-induced degradation kinetics of hydrogenated polymorphous silicon (pm-Si:H) solar cells having either substrate or superstrate device configuration. Both types of devices were exposed to light-soaking for 500 h. While pm-Si:H superstrate solar cells showed strong degradation (up to 60%) under mercury vapor lamp illumination, we have found that substrate structures are remarkably stable. The difference between the two types of devices is shown to be related to interface delamination which only occurs in superstrate devices. We further demonstrate a strong correlation between short-circuit current density decrease upon light-soaking and solar cell area loss.

1. Introduction

Evidence of the progress in hydrogenated amorphous silicon (a-Si:H) solar cell technology includes recent state-of-art triple junction solar cells on stainless steel (substrate configuration) with initial efficiency values ($\eta_{initial}$) of 16.3% [1], and a stabilized efficiency (η_{stable}) of 13.4% [2] for similar cells on glass substrates (superstrate configuration). These results underline the potential of a-Si:H based solar cells to compete with multicrystalline silicon devices at far lower costs. However, the main barrier to higher efficiencies for these devices continues to be the light-induced degradation of their a-Si:H top cell, also known as the Staebler–Wronski effect (SWE) [3]. One of the strategies to reduce the metastable degradation of the top cell is to replace it with a more stable material, such as proto-crystalline, or "on the edge" a-Si:H. Another option being explored is the use of hydrogenated polymorphous silicon (pm-Si:H), consisting of a small volume fraction of nanocrystals embedded in an amorphous matrix presenting medium range order [4]. Contrary to proto-crystalline or on-the-edge a-Si:H films, the crystalline fraction in pm-Si:H originates from plasma-generated silicon nanocrystals, and so the material does not evolve with thickness. It has been shown that this material is more resistant to light-induced defect creation than a-Si:H [5], and early studies demonstrated excellent solar cell stability (at 9.4%) under red light soaking [6]. However, further

studies revealed that pm-Si:H superstrate solar cells show unusual light-induced degradation kinetics, such as irreversible degradation [7], relaxation of internal stress [8], and light-induced hydrogen migration and interface delamination at the TCO/p-layer interface [9] when submitted to standard AM1.5 light-soaking. Therefore, even if the pm-Si:H material itself is more stable than a-Si:H [6], its incorporation as the active layer in superstrate solar cells did not yield the expected stable devices due to the delamination effects. This is a phenomenon which has also been reported for a-Si:H superstrate solar cells when exposed to extreme light soaking conditions (50 suns and 130 °C) [10,11]. The aim of this study is to further address the "device architecture-vs.-material quality" issue surrounding light-induced degradation. Indeed, data on interface delamination [8,9] and irreversible degradation [7] suggest that there is something more than the standard SWE occurring in superstrate solar cells; besides dangling bonds creation, large structural changes and interface delamination in device scale may play a crucial role on final cell efficiency. This point has been previously raised in previous studies showing a striking difference in hydrogen effusion spectra between p/i and n/i layer stacks [12], which if relevant for p–i–n and n–i–p stacks could strongly affect the solar cell stability. Based on our previous understandings, here we suggest a practical solution on the interface delamination, by inverting the device stack sequence, from superstrate (p–i–n) to substrate (n–i–p).

2. Experiments

In this work, a-Si:H and pm-Si:H superstrate solar cells were deposited at 175 °C by the radio-frequency (RF, 13.56 MHz) glow

* Corresponding author at: Bldg. #102, Room #201-4, KIER-UNIST Advanced Center for Energy, UNIST, 100 Banyeon-ri, Eonyang-eup, Ulju-gun, 689-798 Ulsan, South Korea. Tel.: +82 (0)10 7929 0519.
E-mail address: ka-hyun.kim@kier.re.kr (K.-H. Kim).

discharge technique in a multiplasma-monochamber reactor [14]. Standard a-Si:H was obtained by the dissociation of pure silane at a pressure of 50 mTorr and a RF power of 1 W. Intrinsic pm-Si:H layers were deposited by the dissociation of hydrogen–silane gas mixtures under a total pressure of 2 Torr. The intrinsic pm-Si:H layers were deposited at various RF powers (5–10 W), and for some superstrate cells we varied the thickness of the intrinsic layer. The intrinsic layer thickness was determined by spectroscopic ellipsometry on co-deposited layers on glass, and their deposition rates at each deposition conditions are found to be 1 Å/s for a-Si:H, 1.5 Å/s for pm-Si:H deposited at 5 W, and 5 Å/s for pm-Si:H deposited at 10 W. The superstrate solar cells have the following structure: glass/textured SnO_2:F/p-type hydrogenated amorphous silicon carbon (a-SiC:H)/a-SiC:H buffer/intrinsic layer/n-type a-Si:H/Al contact. The substrate solar cells have an inverted structure, i.e. glass/textured SnO_2:F/n-type a-Si:H/intrinsic layer/p-type microcrystalline silicon oxide (μc-SiO$_x$)/p-type microcrystalline silicon (μc-Si:H)/ITO contact. The reason of different p-type layers of superstrate and substrate structures come from the different TCO contacts. In the superstrate structure, the p-type a-SiC:H layer is directly deposited on Asahi U type SnO_2:F substrate. Otherwise, use of hydrogen diluted gas mixture for the p-type μc-SiO$_x$ deteriorates SnO_2:F substrate, because SnO_2:F is vulnerable under hydrogen plasma. In the substrate structure, a 100 nm thick ITO top contact is deposited on the p layer side. In this case, the p-type layer should be highly conductive because 100 nm thick ITO layer does not provide enough conductivity as 1 μm thick SnO_2:F. All the solar cells are characterized and light-soaked with light shining through p-type layer side. Owing to application of highly transparent p-type μc-SiO$_x$ layer and of optimized light trapping, the pm-Si:H substrate solar cells show high J_{sc} of 15.5 mA/cm^2. For current–density–voltage ($J(V)$) measurements, the solar cells are connected to a Keithley 2400 source meter, and the current was measured while the voltage was swept. The illumination was homogeneous and the solar cells are positioned at the center of the illuminated spot of a Newport Oriel Sol3A solar simulator. In order to minimize the error originating from the small area of the cells (0.03 cm^2), only the defined area of the solar cell is illuminated while the rest of the sample is covered by a metal shadow mask. For each $J(V)$ measurement, six individual solar cells on a 2.5 × 2.5 cm^2 substrate are measured and the solar cell parameters are averaged. The maximum and minimum values are reflected by error bars. For the study of light-induced degradation, sets of $J(V)$ measurements at various stages of light-soaking (LS) were performed. Between each $J(V)$ measurement, the solar cells were light-soaked under open-circuit condition using a mercury-vapor lamp (Hg lamp) providing an intensity of 100 mW/cm^2. The Hg lamp was chosen due to the advantages of a long bulb lifetime, in spite of the spectral mismatch with the AM1.5 standard. The emission spectrum of the Hg lamp mainly consists of UV–blue light, as well as intense emission lines in the visible region [15]. The lamp intensity was calibrated with a commercial crystalline silicon reference solar cell. During LS, the solar cells were fan-cooled to reduce illumination-induced heating. The temperature of the solar cells was monitored using a PT100 thermometer during LS, verifying that the device temperature stayed under 50 °C. After 500 h of LS, the solar cells were annealed at 160 °C for two hours in order to test the reversibility of the light-induced degradation.

3. Results and discussion

Fig. 1 shows the averaged evolution of solar cell parameters for a set of six superstrate and substrate solar cells during LS under Hg lamp illumination. There is notable difference in light-induced
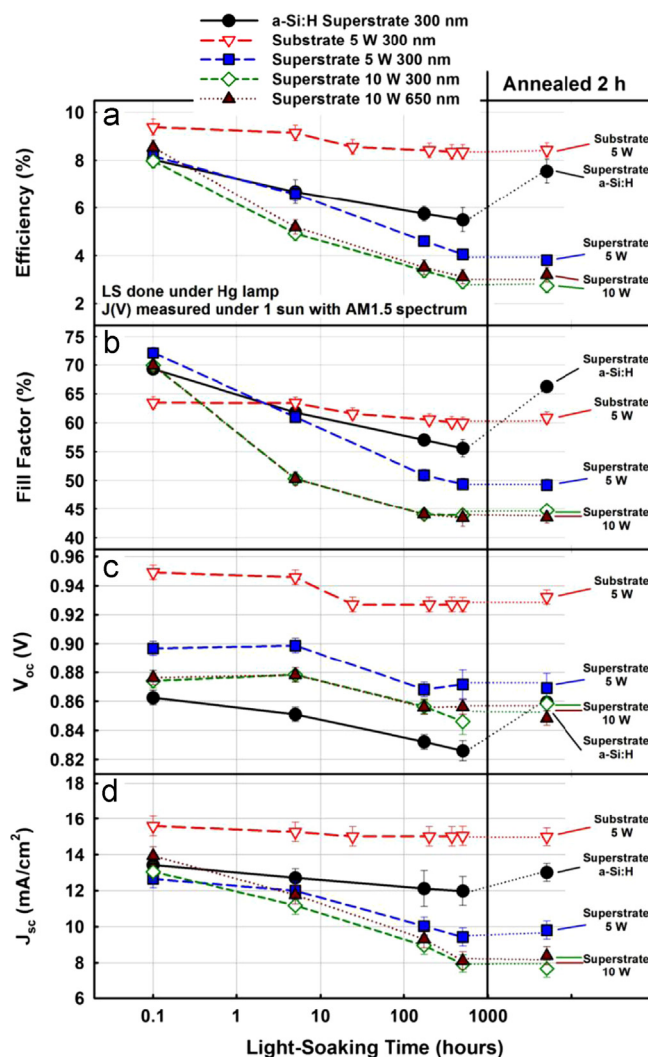

Fig. 1. Evolution of solar cell parameters of selected superstrate and substrate solar cells (a) η, (b) FF, (c) V_{oc}, and (d) J_{sc} during the LS under an Hg lamp illumination. Note that various individual solar cells (up to six) on the 2.5 × 2.5 cm^2 substrates were measured and the solar cell parameters are averaged. The maximum and minimum values are reflected in error bars. Al is used as back-reflector in superstrate solar cells, and ITO is used in substrate. After the LS, the cells are annealed (at 160 °C for 2 h) and checked for reversibility of the light-induced degradation.

degradation kinetics compared to our earlier studies where we found a much smaller degradation for pm-Si:H superstrate solar cells exposed to AM1.5 light soaking for 10 h [7,9]. While the efficiency remained at 7% under AM1.5 light-soaking, the results presented in Fig. 1 show that the efficiency can degrade down from $\eta_{initial}$ of about 9% to η_{stable} of 3% in the worst case under Hg lamp illumination. Such lack of stability for the pm-Si:H superstrate solar cells can be attributed to the spectrum of the LS illumination. Note that in contrast with earlier work where pm-Si:H superstrate solar cells were found to be especially stable under filtered red illumination [6,7], the UV–blue light-rich emission spectrum of the Hg lamp causes an accelerated degradation in the pm-Si:H superstrate solar cells. Such strong dependence of the light-induced degradation on the spectrum of the light is under study.

Further examining the data of Fig. 1 for the two superstrate solar cells deposited under a RF power of 10 W, one can see that their η_{stable} does not depend on the intrinsic layer thickness. Indeed, the two devices with intrinsic layer thicknesses of 300 and 650 nm show the same stabilized efficiency and time