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Letter

Broadband near-field effects for improved thin film Si solar cells on randomly textured substrates

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ABSTRACT

We show the superior performance in terms of light management of n-doped mixed phase silicon oxide in direct contact with Ag with respect to the established ZnO/Ag back reflector in thin film Si tandem solar cells on randomly textured substrates. Based on coexisting larger quantum efficiency and amplification of the optical Raman mode of Si, we propose that, in spite of a simple cell design, near-field concentrated light radiated at metal nanoprotrusions on the back interface is harvested. The effect is a remarkable 10% increase of the generated current density in the bottom cell, holding promise for significant conversion efficiency gain in matched devices.

1. Introduction

Thin film silicon solar cell technology, with its potential to reduce material and fabrication costs, is considered as a promising approach for a large-scale deployment of photovoltaics. When using thin photon absorbers, however, light trapping is crucial to realize high efficiency solar cells. In prospect, advanced three-dimensional designs and photon management strategies based on properly engineered photonic and plasmonic nanostructures have then gained tremendous interest [1–6]. Presently, for a broadband optical enhancement the cells rely on light scattering and diffraction at randomly textured interfaces, for which different morphologies and scattering characteristics are being explored [2,7–12], combined with a back reflector. The pyramidal morphology in particular, also employed in large-area module production, has demonstrated outstanding light trapping capabilities until now leading to certified world-record conversion efficiencies [13]. Fig. 1 shows a common architecture for the micromorph tandem case. This tandem cell, one of the more efficient thin film Si cell concepts, is a series of a high-gap (1.75 eV) amorphous silicon (a-Si:H) top cell and low-gap (1.1 eV) microcrystalline silicon (μc-Si:H) bottom cell, with the two materials almost perfectly matched to efficiently share the spectral content of the sunlight [12–14]. The back reflector also plays an important role, as it has to bring back the un-absorbed light efficiently where it can still be used. One of the conventional solutions makes use of a rear metal layer like Ag. In this case a low refractive index buffer layer, like doped ZnO, is generally inserted between Si and Ag to avoid losses in reflected light due to the excitation of surface plasmon polaritons (SPPs), travelling waves of surface charge density at the metal/dielectric interface. These losses fall in the spectral region where optimum reflectance is desired and the role of the spacer is to shift the SPP dispersion relation, moving the plasmon frequencies toward higher energies (essentially already absorbed in the front part of the cell) [15]. In previous work, phosphorous-doped mixed phase silicon oxide (n-SiO_x:H), thanks to a sufficiently low refractive index, has shown similar capabilities and it has been then proposed as an advanced n-layer for thin film Si solar cells [16,17]. This material class, with independently tunable electrical and optical properties, is demonstrating interesting light management capabilities, and various versions are now being successfully used as superior doped layers and/or reflecting layers in multijunction thin-film Si solar cells [18–20]. Here we have taken the concept introduced in Refs. [16,17] further to show the superior performance in terms of light management of the n-SiO_x:H/Ag combination with respect to the already established ZnO/Ag back reflector. A remarkable 10% increase of the current density generated in the bottom cell of micromorph devices is reported. Based on a concurrent Raman amplification effect, we propose that the thin n-SiO_x:H layer, by keeping the Si absorber layer sufficiently close to the Ag contact, permits also the absorption of near-field concentrated light re-radiated by the nanotextured metal surface due to localized phenomena [21–24]. With the appropriate materials, even with random

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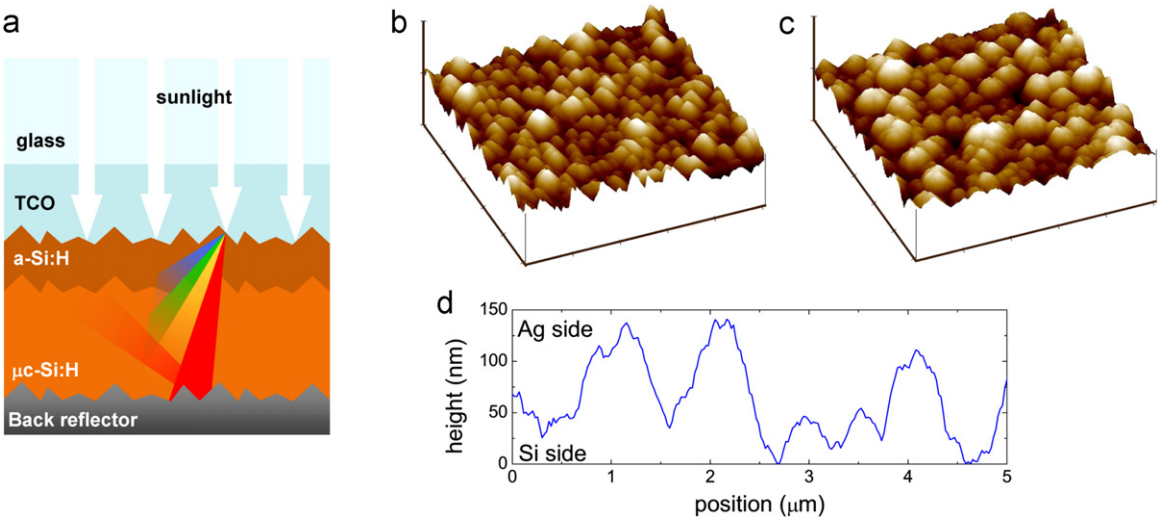

Fig. 1. (a) Schematic representation of the micromorph solar cell architecture in superstrate (p–i–n) configuration with randomly nanostructured front and back contacts (TCO stands for transparent conducting oxide); (b,c) AFM topographic images (image size 5 μm × 5 μm and *z* axis 300 nm/div) of the nanoscale texture of the Asahi U substrate used in this work (b) and of the back surface of the entire Si stack (c); (d) representative profile along a randomly chosen line on the map in (c), showing the characteristic dimensions of the back contact protrusions toward the Si layers.

morphologies localized phenomena could then be exploited with remarkable effect in the solar cell efficiency.

2. Experimental details

Identical superstrate-type micromorph solar cells, including n-SiO_x:H or standard μc-Si:H n-layers (35 nm thick) in the bottom cell, were deposited by plasma-enhanced chemical vapor deposition in a lab-scale reactor on $10 \times 10\ cm^2$ commercial Asahi U-type glass, where randomly textured SnO_2:F acts as transparent conducting electrode. Details on cell fabrication parameters are reported elsewhere [25,26]. Based on the previous work [17], two appropriate mixed phase n-SiO_x:H layers with slightly different stoichiometry were selected. The refractive index (at 800 nm) and electrical conductivity, evaluated on 100 nm thick films deposited on glass, are $n=2.6$, $\sigma=0.2\ (\Omega\,cm)^{-1}$ in one case and $n=2.4$, $\sigma=5\times10^{-3}\ (\Omega\,cm)^{-1}$ in the other. TnSiO1 and TnSiO2 are the corresponding tandem solar cells employing these materials in the bottom cells, while TnSi is the tandem device with standard μc-Si:H n-layer [$n=3.3$ at 800 nm and $\sigma=0.1\ (\Omega\,cm)^{-1}$]. For the back reflecting contact two classical options were considered: a single evaporated Ag layer or sputtered Al doped ZnO (80 nm thick) followed by evaporated Ag, realized on p–i–n/p–i–n Si stacks grown in the same run to allow direct comparison. In order to enlarge the spectral range where the back reflector effects are observable, reduced absorber layer thicknesses were adopted: 140 nm for the a-Si:H top cell and 720 nm for the μc-Si:H bottom cell, for a total device thickness of ~1 μm (including all the Si-based layers). For each design, $1 \times 1\ cm^2$ cells were defined at the back contact realization stage by using a metal mask.

External quantum efficiencies EQEs of the a-Si:H top and μc-Si:H bottom cells were measured under red and blue bias light illumination, respectively. The corresponding short-circuit current densities J_{sctop} and J_{scbot} were calculated from the EQE curves by convolution with the photon flux of the global air mass 1.5 (AM1.5 g) solar spectrum. The current density–voltage $J(V)$ characteristics, from which the open-circuit voltages V_{oc} and the fill factors FF were determined, were measured using a dual lamp solar simulator in standard test conditions (25 °C, AM1.5 g, 1000 W/m^2). Complementary Raman measurements have been carried out on the devices with a Renishaw inVia Reflex Raman spectrometer.

3. Results and discussion

The devices, whose structure is schematized in Fig. 1(a), are characterized by nanostructured front and back contacts. Topographic images of the rough surfaces acquired by Atomic force microscopy (AFM) are shown in Fig. 1(b) and (c). Since each subsequent layer is conformally deposited, the underlying pyramidal structure of the substrate shown in Fig. 1(b) (measured root mean square roughness of 32 nm) is transferred to the other interfaces with similar features [Fig. 1(c)]. The metal back contact, the negative of Fig. 1(c), is then characterized by random surface protrusions extending toward the Si stack with heights up to ~100 nm and wide apex divergence angles, as visualized by the representative profile in Fig. 1(d). The performance metrics of the different cells are summarized in Table 1. For all the cells open circuit voltage V_{oc} and fill factor FF are close to state-of the-art values, while the thin absorber layers limit the efficiencies η in between 8.2% and 9.4%, due to the reduced short circuit current densities. With a top cell current of ~10 mA/cm^2, the desired current matching between the two series-connected subcells is more or less achieved for the devices with ZnO, while with single Ag reflector TnSi is bottom limited and TnSiO1 and TnSiO2 are top limited. The share of the various wavelengths to the generated current for all the cells is shown in Fig. 2. The spectral response of the top cell, that absorbs mostly the blue and green part of the spectrum between 350 and 800 nm, is very similar in all cases, as the top cells were designed to be identical. Even if the same absorber layer thickness was considered, the contribution from the bottom cell, absorbing from 500 to 1100 nm, is instead very different due to the different management of the long wavelengths light. The known beneficial effect of the ZnO spacer in the standard cell (TnSi) is evident. A similar role is played by n-SiO_x:H [17], but interestingly a superior response is achieved in the absence of ZnO, while the EQE of all the cells with ZnO is similar independently of the type of n-layer. This effect has been observed for all the cells realized on the substrate and confirmed by analogous devices realized in different deposition runs. Clearly