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An intrinsic amorphous silicon oxide and amorphous silicon stack passivation layer for crystalline silicon heterojunction solar cells

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ABSTRACT

Intrinsic amorphous silicon oxide (i-a-SiO:H) films were used as passivation layers in crystalline silicon heterojunction (c-*Si*-HJ) solar cells. The effective lifetime (τ_{eff}) and photovoltaic (PV) parameters were improved by controlling the CO_2/SiH_4 ratio in the i-a-SiO:H rear passivation layer. The enhancement of the open circuit voltage (V_{oc}) and solar cell efficiency (η) caused by the i-a-SiO:H/i-a-Si:H stack passivation layer was investigated. The c-*Si*-HJ solar cells using an i-a-SiO:H/i-a-Si:H stack passivation layer showed a high V_{oc} and η compared to using a conventional i-a-SiO:H passivation layer. The highest efficiency obtained for a c-*Si*-HJ solar cell using an i-a-SiO:H/i-a-Si:H stack passivation layer was 19.4% (V_{oc} = 715 mV, J_{sc} = 34.9 mA/cm^2, FF = 0.78).

1. Introduction

At present, crystalline silicon (c-Si) solar cells have a lifetime reliability and high performance [1–3]. Amorphous silicon/crystalline silicon (a-Si:H/c-Si) heterojunction solar cells are also interesting because their structures have developed and achieved a high conversion efficiency [4–6]. Moreover, the low temperature coefficients (TCs) of crystalline silicon heterojunction (c-*Si*-HJ) solar cells, when suitably applied in a high temperature environment, have resulted in higher energy yields (Y_f) when compared to conventional c-Si homojunction solar cells [7,8]. Generally, the structure of c-*Si*-HJ solar cells contains intrinsic hydrogenated amorphous silicon (i-a-Si:H) thin films deposited on the front and rear sides of the silicon wafer for surface passivation, a doped silicon thin film for the emitter and back surface field (BSF), a transparent conductive oxide (TCO) and metal contacts. In c-*Si*-HJ solar cell structure, the surface passivation of c-Si was a key technology to achieve high open circuit voltage (V_{oc}) and solar cell efficiency (η). The effective minority carrier lifetime (τ_{eff}) was mainly influenced by the front passivation layer, but the rear passivation layer also significantly reduced surface recombination. The effective minority carrier lifetime can be described as follows:

$$1/\tau_{eff} = 1/\tau_{bulk} + 1/\tau_{front} + 1/\tau_{rear} \quad (1)$$

where τ_{bulk} is the bulk lifetime, and τ_{front} and τ_{rear} are the front and rear surface lifetimes, respectively. However, epitaxial growth during the deposition of i-a-Si:H has been observed, which deteriorated surface passivation [9–11]. This problem resulted in lowered V_{oc} and performance of the c-*Si*-HJ solar cell. Therefore, an improvement of surface passivation for c-Si was needed to enhance the performance of c-Si-HJ solar cells. To obtain a high-quality surface passivation layer, several methods have been demonstrated, such as amorphous-to-microcrystalline transition phase [12,13], H_2-plasma treatment (HPT) [14,15], a passivation layer deposited from hot-wire chemical vapor deposition (HWCVD) [16,17], electron cyclotron resonance chemical vapor deposition (ECRCVD) [18,19], and post-deposition annealing [20–22]. In addition, a wide bandgap hydrogenated silicon oxide material was a good alternative for the passivation layer because hydrogenated amorphous silicon oxide (a-SiO:H) could suppress epitaxial growth and low light absorption [23,24]. In this paper, we investigated the effect of an i-a-SiO:H rear passivation layer and an i-a-SiO:H/i-a-Si:H stack layer for surface passivation on c-*Si*-HJ solar cell performance.

2. Experimental details

Soda-lime glass and mono crystalline silicon wafers were used as substrates for the i-a-Si:H and i-a-SiO:H film depositions. As-cut Czochralski method (CZ) c-Si solar-grade n-type wafers with a (100) orientation, a resistivity range of 1–5 Ω·cm, and a thickness of 180 μm were used for this experiment. Saw damage on the silicon wafer surface

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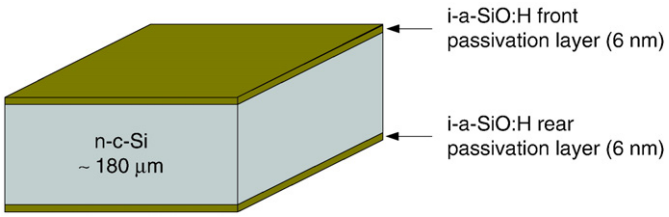

Fig. 1. Schematic structure of lifetime sample.

was removed by a potassium hydroxide (KOH) wet chemical process [25–27], and it was then cleaned by a Radio Corporation of America (RCA) process to remove organic and metallic contaminants [28,29]. Glass substrates were cleaned by a sequence of isopropanol, acetone and isopropanol. Silicon thin films were deposited using a multichamber plasma-enhanced chemical vapor deposition (PECVD) system. The i-a-SiO:H films used a gas mixture comprising silane (SiH_4), hydrogen (H_2) and carbon dioxide (CO_2) with a very high-frequency (60 MHz) PECVD, a substrate temperature of 180 °C, a plasma power density of 20 mW/cm^2 and a deposition pressure of 300 mTorr. The samples for lifetime measurement were prepared by depositing the i-a-Si:H and i-a-SiO:H films on both sides of the silicon wafer, and passivation quality was measured in terms of the effective carrier lifetime, which used the quasi-steady-state photoconductance (QSSPC) method to evaluate the minority-carrier lifetime [30,31]. The schematic structure of a sample for lifetime measurement is shown in Fig. 1. Meanwhile, the optical properties and thickness of these i-a-Si:H and i-a-SiO:H films deposited on glass substrates were examined by spectroscopic ellipsometry (SE).

The c-*Si*-HJ solar cells were fabricated using i-a-Si:H, i-a-SiO:H and an i-a-SiO:H/i-a-Si:H stack as passivation layers. The schematic structure of the c-Si-HJ solar cells used to verify the effect of the passivation layer on the photovoltaic (PV) parameters is shown in Fig. 2. A microcrystalline silicon oxide p-type (p-μc-SiO:H) film was used as an emitter layer with a thickness of 30 nm. Additionally, the a-Si:H n-layer was used as a back surface field with a thickness of 30 nm. Indium tin oxide (ITO) was used as the TCO, deposited via direct current (DC) magnetron sputtering with a thickness of 80 nm. The metallization process of the front and back metal contacts used the silver and aluminum evaporation method. The effective lifetime of the solar cells was measured before the ITO film and metal contact deposition. The total solar cell area was 1 cm^2 (active area of 0.96 cm^2). The current-voltage (*I-V*) characteristics and PV parameters of the solar cells were measured under standard conditions (AM 1.5, 100 mW/cm^2, 25 °C) using a xenon and halogen light source solar simulator. The quantum efficiency (QE) of the solar cells was characterized using the spectral response measurements.

3. Results and discussions

To improve the passivation quality of n-c-Si, the effect of the CO_2/SiH_4 ratio on the rear surface passivation quality of the i-a-SiO:H films was investigated. i-a-SiO:H films with a CO_2/SiH_4 ratio of 0.2 were

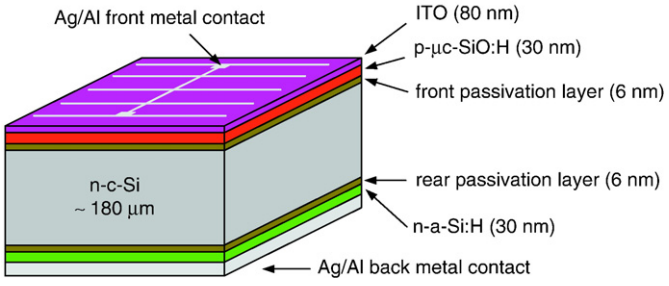

Fig. 2. Schematic structure of c-*Si*-HJ solar cell.

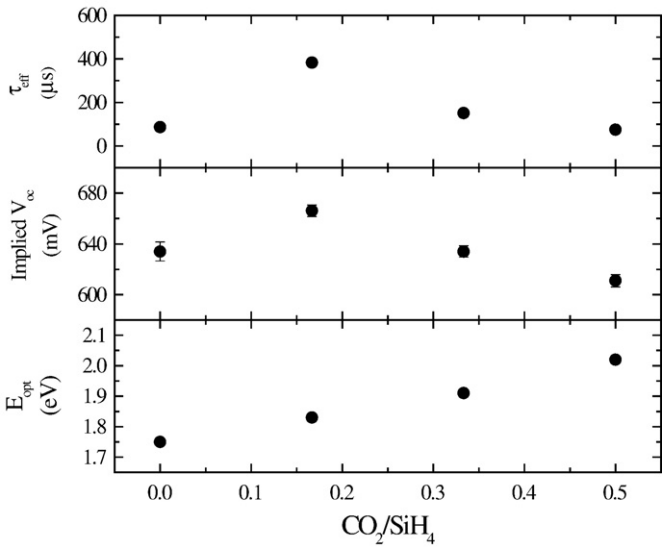

Fig. 3. Effective lifetime (τ_{eff}), implied (V_{oc}) and optical bandgap (E_{opt}) of the i-a-SiO:H films were a function of the CO_2/SiH_4 ratio for rear passivation layer.

deposited on front side of the silicon wafers, while the CO_2/SiH_4 ratio of the rear side was varied from 0.0 to 0.5. The sample structure was fabricated as the i-a-SiO:H front passivation layer (CO_2/SiH_4: 0.2)/n-c-Si/i-a-SiO:H rear passivation layer (CO_2/SiH_4: 0.0–0.5). The thickness of the i-a-SiO:H films was 6 nm. The results showed that the CO_2/SiH_4 ratio of the i-a-SiO:H passivation layers affected the τ_{eff} of the silicon wafers, as shown in Fig. 3. For the CO_2/SiH_4 ratio of 0.0, the sample showed a low τ_{eff} of 86 μs, which might affect whether the i-a-Si:H layer grew an epitaxial silicon layer on the silicon wafer surface [32–34]. Increasing the CO_2/SiH_4 ratio from 0.0 to 0.17, the τ_{eff} increased rapidly from 86 μs to 382 μs and then declined to 74 μs with the CO_2/SiH_4 ratio of 0.5. The increase in oxygen content during the film deposition affected the increase in the defect density [35,36]. Meanwhile, the implied V_{oc} increased from 634 mV to 666 mV, with the CO_2/SiH_4 ratio increasing from 0.0 to 0.17, and decreased to 611 mV with the CO_2/SiH_4 ratio of 0.5, which corresponded with the τ_{eff} values. Additionally, the optical bandgap (E_{opt}) of the i-a-SiO:H films gradually increased with the increasing CO_2/SiH_4 ratio because of the oxygen atoms incorporating into the i-a-SiO:H films. The optical bandgap of the i-a-Si:H film with the CO_2/SiH_4 ratio of 0.0 was 1.75 eV. Then, the optical bandgap of the i-a-SiO:H films increased from 1.83 eV to 2.02 eV, with the CO_2/SiH_4 ratio increasing from 0.17 to 0.50, respectively. The optical band gap became wider because of more *Si*—O bonds in the amorphous silicon oxide phase.

The effect of the CO_2/SiH_4 ratio of the i-a-SiO:H rear passivation layer on the solar cell performance was studied. The CO_2/SiH_4 ratio of the i-a-SiO:H rear passivation layer was varied from 0.0 to 0.50 with the thickness maintained at 6 nm. Fig. 4 shows the PV parameters and τ_{eff} as a function of the CO_2/SiH_4 ratio for the i-a-SiO:H rear passivation layer. The solar cells showed a low V_{oc} of 684 mV at the CO_2/SiH_4 ratio of 0.0 but a high fill factor (*FF*) of 0.78. The V_{oc} increased from 684 mV to 692 mV, with the CO_2/SiH_4 ratio increasing from 0.0 to 0.17, and decreased to 675 mV with the CO_2/SiH_4 ratio of 0.5, which aligned with the τ_{eff} values. Meanwhile, the *FF* tended to decrease with the increasing CO_2/SiH_4 ratio. Fig. 5 shows the *I-V* characteristics of c-*Si*-HJ solar cells with various CO_2/SiH_4 ratios of the i-a-SiO:H rear passivation layer. The *I-V* values of the solar cells showed a tilt curve because of the increased series resistance in the films with increasing CO_2/SiH_4 ratios in the i-a-SiO:H rear passivation layer [37–39]. These results indicate that control of the CO_2/SiH_4 ratio could improve the rear surface passivation quality and solar cell efficiency, indicating that the i-a-SiO:H film has potential to be applied for the rear surface passivation of a c-*Si*-HJ