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A buffer-layer/a-SiO$_x$:H(p) window-layer optimization for thin film amorphous silicon based solar cells[☆]

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ABSTRACT

Amorphous silicon based (a-Si:H-based) solar cells with a buffer-layer/boron doped hydrogenated amorphous silicon oxide (a-SiO$_x$:H(p)) window-layer were fabricated and investigated. In the first part, in order to reduce the Schottky barrier height at the fluorine doped tin oxide (FTO)/a-SiO$_x$:H(p) window-layer heterointerface, we have used buffer-layer/a-SiO$_x$:H(p) for the window-layer, in which boron doped hydrogenated amorphous silicon (a-Si:H(p)) or boron doped microcrystalline silicon (μc-Si:H(p)) is introduced as a buffer layer between the a-SiO$_x$:H(p) and FTO of the a-Si:H-based solar cells. The a-Si:H-based solar cell using a μc-Si:H(p) buffer-layer shows the highest efficiency compared to the optimized bufferless, and a-Si:H(p) buffer-layer in the a-Si:H-based solar cells. This highest performance was attributed not only to the lower absorption of the μc-Si:H(p) buffer-layer but also to the lower Schottky barrier height at the FTO/window-layer interface. Then, we present the dependence of the built-in potential (V_{bi}) and blue response of the devices on the inversion of activation energy (ξ) of the a-SiO$_x$:H(p), in the μc-Si:H(p)/a-SiO$_x$:H(p) window-layer. The enhancement of both V_{bi} and blue response is observed, by increasing the value of ξ. The improvement of V_{bi} and blue response can be ascribed to the enlargement of the optical gap of a-SiO$_x$:H(p) films in the μc-Si:H(p)/a-SiO$_x$:H(p) window-layer. Finally, the conversion efficiency was increased by 22.0%, by employing μc-Si:H(p) as a buffer-layer and raising the ξ of the a-SiO$_x$:H(p), compared to the optimized bufferless case, with a 10 nm-thick a-SiO$_x$:H(p) window-layer.

1. Introduction

Wide band gap hydrogenated silicon alloys have become one of the most promising materials for the mass production of low-cost photovoltaic cells for terrestrial power applications [1]. Wide band gap hydrogenated p-type amorphous silicon carbide was developed by the Hamakawa group as a window material, to replace the narrow band gap p-type hydrogenated amorphous silicon [a-Si:H(p)]. The use of wide band gap window material has opened a way for high performance amorphous silicon based (a-Si:H-based) solar cells [2]. In comparison with conventional p-i-n a-Si:H-based solar cells, wide band gap hydrogenated silicon alloy/intrinsic hydrogenated amorphous silicon (a-Si:H(i)) heterojunction is attributed to higher built-in potential (V_{bi}), and then to higher open-circuit voltage (V_{oc}). In addition, the external quantum efficiency in the blue region of the spectrum is improved due to the high transparency in this region of high band gap materials [3,4]. However, because of the abrupt band gap discontinuity and mismatch originating from the hydrogenated silicon alloy ($E_g \approx 2.0$ eV)/a-Si:H(i)) ($E_g \approx 1.72$ eV) heterojunction, a thin highly defective zone several nanometers thick with a short carrier lifetime is formed at the interface [4,5]. This defective heterojunction interface limited the cell performance due to a consideration of a recombination loss of photogenerated carriers at the interface [6]. Several ways have been developed to reduce p/i interface recombination loss. The use of carbon-alloy graded or constant band gap a-SiC:H layers inserted between the a-SiC:H and a-Si:H(i) layer was reported [3–7]. Alternative techniques related to hydrogen plasma treatment; and photo-assisted hydrogen radical treatments at the p/i interface were also reported by a few other groups [6–8].

The work function difference between the transparent conductive oxide (TCO) and a hydrogenated silicon alloy layer, another drawback of using wide band gap hydrogenated silicon alloy, causes a band bending effect and builds a high interface potential barrier, which impeded the extraction of photogenerated holes from the a-Si:H(i) layer

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[9]. The transmission of photogenerated holes is accumulated at the interface and the recombination of photogenerated electrons diffusing back toward the TCO interface is enhanced, leading to a deterioration of the fill factor (FF) [10]. Commonly, to reduce the interface potential barrier, the high conductive buffer-layer such as amorphous diamondlike carbon, amorphous silicon carbide, and microcrystalline silicon can benefit solar cell performance by enhancing hole collection by lowering the interface potential barrier [11]. However, a related silicon carbide material has some disadvantages due to the contamination of the carbon [10]. The use of an amorphous tungsten oxide layer at a TCO/p interface as a buffer-layer, resulting in the improvement of V_{oc}, due to the Schottky barrier height lowering, was also suggested [11]. Currently, Lee et al. reported that AZO/a-SiC:H(p) can get better contact properties with the insertion of a highly conductive a-Si:H(p) or boron-doped microcrystalline silicon (μc-Si:H(p)) layer. This insertion reduced the series resistivity at the AZO/a-SiC:H(p) interface, and built an Ohmic contact, which in turn improves the FF [12,13]. In their investigation, however, it looks like the devices' performance suffered a lot due to the deterioration of short-circuit current density (J_{sc}), which is one of the key factors for a high efficiency a-Si:H-based solar cell.

In this paper, the dependence of the a-Si:H-based solar cells' performances on buffer-layer/a-SiO_x:H(p) window-layers in the TCO/buffer-layer/a-SiO_x:H(p)/a-Si:H(i) heterojunction was investigated. The fabrication of a-Si-based silicon solar cells, by introducing an a-Si:H(p) or μc-Si:H(p) as a buffer-layer between a TCO and a-SiO_x:H(p) interface, is reported, in order to reduce the front interface potential barrier, and in turn enhance the a-Si based solar cell performance. Then, the dependence of the built-in potential and blue response of the device on the inversion of activation energy (ξ), $\xi = E_g - E_a$, of the a-SiO_x:H(p) in the μc-Si:H(p)/a-SiO_x:H(p) window-layer is discussed.

2. Experimental details

Thin film a-Si:H-based solar cells were fabricated by cluster plasma enhanced chemical vapor deposition, using power sources with a radio frequency of 13.56 MHz (for the a-Si:H(p)-layer, μc-Si:H(p)-layer, a-SiO_x:H(p)-layer and a-Si:H(n)-layer), and a very high frequency of 60 MHz (for the a-Si:H(i)-layer). Prior to a-Si:H deposition, the fluorine doped tin oxide (FTO)-coated glass substrates were cleaned sequentially, using acetone, isopropyl alcohol, and deionized water for 10 min each. The deposition condition for a-Si:H(p) buffer-layer, μc-Si:H(p) buffer-layer, a-Si:H(i), and a-Si:H(n) are summarized in Table 1; while the deposition condition for different a-SiO_x:H(p) window layers were as follows: nitrous oxide flow rate was varied by maintaining hydrogen dilution, and the B_2H_6 to SiH_4 flow rate. The detail deposition condition of a-SiO_x:H(p) can be found in Table 2. The device structure was glass/FTO-800 nm/buffer-layer-5 nm/a-SiO_x:H(p)/a-Si:H(i)-350 nm/a-Si:H(n)-25 nm/aluminum-electrode-300 nm, in which the thickness of the a-SiO_x:H(p) layer was fixed at 10 nm and 5 nm for without and with incorporation of buffer-layer, respectively.

The optoelectronic properties of these films were measured. Spectroscopic ellipsometry (VASE, J. A. Woollam, 240 nm < λ < 1700 nm) was used to measure the thickness, and optical band gap at an angle of incidence of 65°, in the spectral range of 240 nm to 1700 nm. The electrical characteristics were studied by the coplanar method, using a programmable Keithley 617 electrometer, using samples grown on glass substrates. The activation energy (E_a) is obtained from the temperature dependent dark conductivity σ_d (T) by the Arrhenius relation [14]

Table 2
Deposition conditions of the a-SiO_x:H(p) with different SiH_4:H_2:N_2O gas ratios.

Sample no.	Gas ratio		Power (W)	Pressure (Pa)	Electrode distance (mm)	Temp. (°C)	ξ (eV)	C(O) at.%
	SiH_4:H_2:N_2O	SiH_4/B_2H_6						
1	1:20:4	0.5	30	93.3	60	180	1.317	3.87
2	1:20:6						1.362	8.05
3	1:20:8						1.425	17.16
4	1:20:10						1.475	22.05

$$\sigma_d(T) = \sigma_o \exp(-E_a/kT) \quad (1)$$

where σ_o is a conductivity prefactor, T is the absolute temperature, and k is Boltzmann's constant. The E_a and σ_d of the a-Si:H(p) and μc-Si:H(p) are presented in Table 1. To estimate the concentration of oxygen (C(O) at.%) within the a-SiO_x:H(p) films Fourier transform infrared spectroscopic (FTIR) measurements were performed on samples deposited on Si wafers, by using FTIR Prestige-21 spectrometer, Shimadzu, in the 7800–350 cm^{-1} wave number range. The asymmetric stretching vibration of oxygen in the Si–O–Si bond form was detected at a wave number of about 1000 cm^{-1} and was used to calculate the oxygen content with the support of a calibration constant from reference [15]. The quantum efficiency (QE) of the solar cells was measured by using a xenon lamp, a monochromator, and optical filters, which filtered out the high orders, with a light probe beam impinging normal on the samples. Finally, the thin film a-Si based solar cells were characterized by current density–voltage measurements under AM 1.5 illumination, with 100 mW/cm^2 light intensity at 25 °C.

3. Result and discussion

3.1. Effect of the buffer-layer between TCO and an a-SiO_x:H(p) heterointerface

Fig. 1 and Table 3 presents the photo illuminated-voltage (I-V) characteristics and solar cell performances for the fabricated p-i-n a-Si:H-based solar cell without and with the incorporation of an a-Si:H(p) or μc-Si:H(p) layer. The V_{oc} of the bufferless cell with a 10-nm-thick a-SiO_x:H(p) wide band gap window-layer was as low as 810 mV. This low value is attributed to the high Schottky barrier height (ϕ_{s1}) formed between the FTO and a-SiO_x:H(p), as shown in Fig. 2. The V_{oc}, the FF and hence efficiency (Eff) were increased by the insertion of the buffer-layers. Especially, improvements are found in FF by 22% and 20% with an incorporation of a-Si:H(p) and μc-Si:H(p), respectively.

To elucidate the reason for V_{oc} and FF improvement, band diagram variation due to the incorporated buffer-layer at the FTO/a-SiO_x:H(p)

Table 1
Deposition conditions of the a-Si:H-based solar cell.

Layer	Gas ratio		Power (W)	Pressure (Pa)	Temp. (°C)	Thickness (nm)	Dep. rate (nm/min)	σ_d (S/cm)	E_a (eV)
	SiH_4:H_2:N_2O	SiH_4/B_2H_6(PH_3)							
a-Si:H(p)	1:5:0	0.05	50	26.6	180	5	6.1	4.64×10^{-7}	0.51
μc-Si:H(p)	1:160:0	1.0	300	13.3	200	5	4.4	3.75×10^{-2}	0.07
a-SO_x:H(p)	1:20:6	0.5	30	93.3	180	10 (5)	3.7	2.4×10^{-7}	0.53
a-Si:H(i)	1:4:0	0	15	26.6	180	350	12.6	6.0×10^{-10}	0.73
a-Si:H(n)	1:4:0	1	50	26.6	200	25	4.6	8.83×10^{-3}	0.204