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Electrical Characterization of Poly-Si Thin Film Solar Cells Deposited on Textured Substrate

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ABSTRACT

Textured substrate widely used for developing high performance poly-Si solar cells, due to surface texture of a transparent conductive oxide (TCO) layer on a glass substrate is usually utilized for the light trapping technique, which achieve a large photocurrent of the poly-Si material. The electrical conductivities of the poly-Si thin films deposited on the substrates with different surface texture have been studied using the alternating current (AC)-conductivity measurement technique. The measurement results show that the activation energy of the dark conductivities for poly-Si films with deposited on relative low of the root mean square (rms) roughness (s) of 22 nm is close to 0.55 eV indicating intrinsic nature. On other hand, with increase in $s > 37$ nm, poly-Si films exhibit n-type character. Changes in electrical conductivities of the poly-Si thin films in conjunction with the results on photovoltaic performances, optical reflectance, and microstructure are also discussed.

Keywords: *Textured substrate, solar cells, thin film, conductivity, electronics characteristics.*

Introduction

The light-trapping technique in poly-Si layer by textured substrate is one of the most important issues for the improvement of the conversion efficiency of solar cells (Green 1987). However, recent studies have revealed that the poly-Si thin film solar cells deposited on the textured substrate show poor photovoltaic performance including the short-circuit photocurrent density (J_{sc}) as well as open circuit voltage (V_{oc}) mainly due to change in the microstructure of poly-Si layer and the carrier transport property which plays a dominant role in determining the photovoltaic performance (Matsui et al. 2002a). So far, there have been only few reports on the optimum design of substrate texture to realize further improvement of the photovoltaic performance of poly-Si solar cells (Matsui et al. 2002c). Especially the characterization of electrical transport of poly-Si thin films deposited on the substrates with different surface texture has not been sufficient performed.

An AC-conductivity measurement technique has been proposed as a powerful tool for measuring the material conductivity with sandwich electrode geometry along the growth direction (Matsui et al. 2002b). Recently, employing the AC-conductivity technique, we have reported that the electron and hole transport properties of the poly-Si thin films made on a flat substrate with different microstructures in conjunction with their photovoltaic performances (Matsui et al. 2002c). We have demonstrated in the chapter III, that the AC-conductivity measurement with our proposed sample structures, i.e., n-i-n and p-i-p, can be applied to determine the individual electron and hole conductivities along the poly-Si growth direction (Matsui et al. 2002c). The poly-Si thin films with relatively low crystalline volume fraction, $X_c \sim 50\%$ exhibit intrinsic character, leading to the successful high efficiency solar cell fabrication. In contrast, poly-Si films with high crystalline volume fraction induce higher film conductivity with n-type character. This effect is proposed to be responsible for the pronounced reduction in the open circuit voltage, V_{oc} .

In this paper, the carrier transport properties of the poly-Si thin films made on various textured substrates are demonstrated (Muhida et al. 2003). The electron and hole conductivities along growth direction as well the Fermi energy estimated from their activation energies are also presented as a function of surface roughness of the textured substrate. Furthermore, correlation of the carrier transport properties with microstructures, photovoltaic performances, and the field-dependent carrier collection is discussed.

Material and Methods

The solar cells have a structure of Ag-grid/ ZnO/p-i-n/ZnO (1000 Å)/Ag(1000 Å)/SnO₂ (6300–25000 Å)/ glass (Matsui et.al. 2002b). A series of substrates of different surface texture was prepared and then used as the back reflector of poly-Si solar cells. For these substrates, a highly reflective ZnO(1000 Å)/Ag(1000 Å) double layer was

formed directly using sputtering process on a SnO₂/glass substrate prepared by Asahi Glass Company. The surface morphology was controlled by the thickness of the SnO₂ layer. Highly conductive microcrystalline silicon was used for doped p- and n-layers, which were deposited by a rf-PECVD (13.56 MHz) system. The undoped poly-Si photovoltaic layer with a thickness of 2.5–3.0 μ m was deposited by another PECVD with a very high frequency plasma enhanced chemical vapor deposition (VHF-PECVD) system using a SiH₄ and H₂ gas mixture. In order to obtain a poly-Si layer with (220) preferential orientation as well as about 50% crystalline volume fractions, which yields relative high photovoltaic performances (Nasuno et.al. 2001) we used the following deposition conditions. The deposition pressure was set at 0.8 Torr, SiH₄ concentration, $[\text{SiH}_4]/([\text{SiH}_4]+[\text{H}_2])$, at 4.5%, the substrate temperature, T_s , at 180°C, the VHF-power density at around 100 mW/cm², and the excitation frequency at 100 MHz. Details of the fabrication procedure and experimental results for the solar cells have been described elsewhere (Matsui et.al. 2002a and Matsui et.al. 2002b).

The surface morphology of substrates was characterized by Park Scientific Instrument atomic force microscopy (AFM). The root-mean-square (RMS) roughness, s is evaluated from the AFM image. The crystalline volume fraction, X_c , was evaluated from the Raman scattering spectrum of the Si-Si TO phonon mode (Nasuno et.al. 2001) and the crystallographic orientation was obtained by X-ray diffraction (XRD) measurements. The current–voltage characteristics of the poly-Si solar cells was measured under Air Mass 1.5 (AM1.5), 100 mW/cm² illumination. External quantum efficiency (QE) spectra of solar cells were measured with a conventional lock-in detection system. Optical reflectance spectra were taken with a double-beam spectrometer. The electronic properties in poly-Si thin film were measured using an AC conductivity measurement with our proposed sample structures, i.e., *n-i-n* and *p-i-p* structures for characterization of the electrical transport (Matsui et.al. 2002a, Vetterl et al. 1999; Wyrsh et al. 2000 and Matsui et al. 2002c).

The AC-conductivity measurement was performed on 2-mm-thick poly-Si i-layers in sample structures consisting of ZnO/*n-i-n*/ZnO/Ag/SnO₂/glass and ZnO/*p-i-p*/SnO₂/glass with the different textured substrates. Deposition conditions for *n*- and *p*- layers are identical with those used for the solar cells. The dark AC-conductivity was measured in the frequency range of 50 Hz – 1 MHz under an applied AC-voltage of 10 mV_{rms}. Since the AC-conductivity spectra involve the effects of carrier depletion at contacts and electrode resistance, the “true” film conductivity of poly-Si layer can be determined at frequencies where the effective permittivity, ϵ_{eff} , approaches a proper value of $\epsilon_{\text{eff}}(\text{Si}) = (Cd/\epsilon_0 S) \approx 12$ [Matsui, T et al. 2002d, Wyrsh, N 2000]. Here, C denotes the capacitance corresponding to the imaginary part of measured admittance spectra, d the sample thickness, ϵ_0 the vacuum dielectric constant and S the sample area. Detail of the AC-conductivity measurement technique has been described elsewhere (Matsui et al. 2002a; Vetterl et al. 1999; Wyrsh et al. 2000 and Matsui et al. 2002c).

Results

Firstly, we want to show the light-scattering performance of the solar cells deposited on the different textured ZnO/Ag/SnO₂/glass substrate, as shown in Fig. 1. With increasing $\square$, the reflectance and spectral fringes due to optical interference at infrared region with wavelengths of > 800 nm monotonously decrease, giving an increase in light-scattering, so that the light trapping effect should be enhanced with increasing.

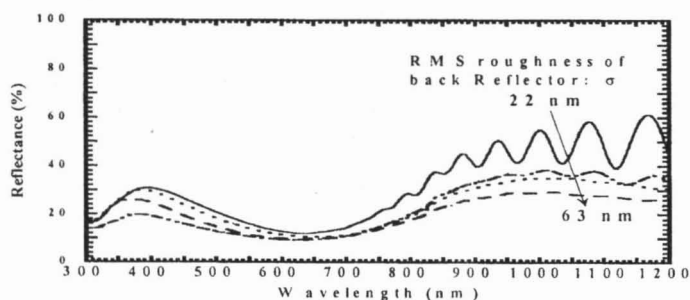


Fig. 1: Reflectance Spectra of the 2.5 μ m Thick Solar Cells Formed on Different Textured ZnO/Ag/SnO₂/glass ($\square$ = 22, 37, 50, 63 nm) Substrate

Figure 2 (a) shows the characteristics of the poly-Si solar cells, short circuit current density J_{sc} , and open circuit voltage V_{oc} as a function of λ of substrate. We can see, with an increase in λ , J_{sc} decrease almost linear, the maximum value about 23 mA/cm² reached at λ of 22 nm, when λ increase the J_{sc} rapidly decreases by about 3 mA/cm², the minimum value reached about 20 mA/cm² for λ 63 nm. The open circuit voltage V_{oc} also shown decrease with increase λ , and reached the minimum value about 445 mV at λ 63 nm.

The Quantum efficiency (QE) spectra response of poly-Si solar cells 2.5 μ m thick solar cells formed on different textured ZnO/Ag/SnO₂/glass (λ =22, 37, 50, 63 nm) substrate at wavelength of 800 nm, as shown in Figure 2 (b).

In order to investigate the influence of substrate texture on poly-Si microstructure, we performed XRD measurements as shown in Figure 2 (c). It shows the XRD patterns of poly-Si layers deposited at different textured substrates. The integrated of the Si (220) diffraction line ($I_{(220)}$) together with its ratio of (220) and (111), $I_{(220)}/I_{(111)}$, which gives a clear indication of a degree of (220) preferential orientation of the poly-Si layer, is plotted against the λ of substrate. All poly-Si thin films basically exhibit (220) preferential orientation with $I_{(220)}/I_{(111)}$ values in the range of 1.2–2.9, however, with increasing the λ , $I_{(220)}$ decrease, and decrease in $I_{(220)}/I_{(111)}$ is mainly due to the decrease in $I_{(220)}$, which give clear indication of the degree of (220) preferential orientation of the poly-Si layer clearly reduces, exhibit low value at $\lambda > 22$ nm. This results implies that microstructure of poly-Si crystallinity deteriorates due to the deposited at high texture substrate tend to become random.

In order to investigate the affect of change in the microstructure to the electronic property due to the change of substrate texture, the activation energy (E_a) of the dark-conductivity measured for poly-Si i-layer deposited on different textured substrate, the activation energy of the dark-conductivity (E_a), which is deducted from the Arrhenius plot at the higher temperature regime (300-400K) which measured for n-i-n, and p-i-p samples (Matsui et al. 2002a; Vetterl et al. 1999; Wyrsh et al. 2000 and Matsui et al. 2002c). Figure 2 (d) shows the activation energy (E_a) of dark conductivities for n-i-n and p-i-p samples as a function of rms roughness substrate (λ), for n-i-n samples shows the activation energy decreases with an increase in λ , and finally reaches ~0.23 eV for λ of 47 nm. On other way, for p-i-p samples show a different, the activation energy increase with an increase in λ , the highest value reached 0.8 eV for λ of 63 nm. From these results, since the activation energy of the dark conductivity is a good approximation of Fermi energies from conduction (valence) band edge, for the textured substrate $\lambda \leq 37$ nm suggests that the Fermi energy locates at the center of the band gap. This, this material is almost intrinsic. For the texture substrate $\lambda > 37$ nm, have the low E_a for electron transport and high E_a for hole transport indicate that the Fermi level is close to conduction band edge and the poly-Si layer on this substrate texture exhibit n-type character. Compare this results with the results of XRD measurement (Figure 2 (c)) suggested that the roughness of the substrate influence the microstructure and electronic transport in poly-Si layer.

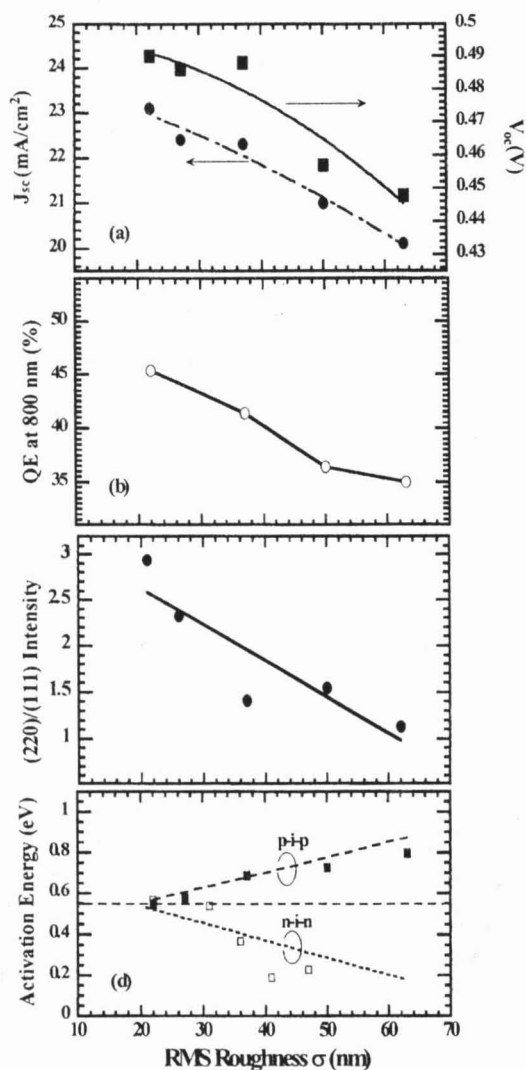


Fig. 2: (a) Photovoltaic Performance J_{sc} and V_{oc} as function of RMS Roughness of Substrate. (b) Quantum Efficiency Spectra (QE) of 2.5 μ m Thick Solar Cells at Wavelength of 800 nm, as function of RMS Roughness of Substrate. (c) Integrated X-ray Diffraction Intensity Ratio $I_{(220)}/I_{(111)}$ as function of RMS Roughness of Substrate. (d) The Conductivity Activation Energies (E_a) as a function of RMS Roughness of Substrate, taken with n-i-n (Open Square) and p-i-p (Close Square) Samples respectively. The lines are guides for eye

As have been presented in Section 3, where the light-trapping performance enhanced with increasing R_{rms} , however, photovoltaic performance is not directly connected with the light-trapping. This indicating that poly-Si crystallinity deteriorates due to the deposited at high textured substrate, as have been shown from XRD measurement in figure 1.c., the poly-Si (220) preferential orientation growth change caused by roughness of substrate surface, the decrease in $I_{(220)}/I_{(111)}$ implicated that poly-Si film tend to grow perpendicular to slanting texture substrate but not to substrate it self. Such diagonally oriented columnar growth may occur the collision with other grains, and then create many grain boundary and related defects, as can be observed in a cross-section of TEM bright field micrograph of the 2.5 μ m thick solar cells deposited at textured $R_{rms}=63$ nm ZnO/Ag/SnO₂/glass substrate in Figure 3.

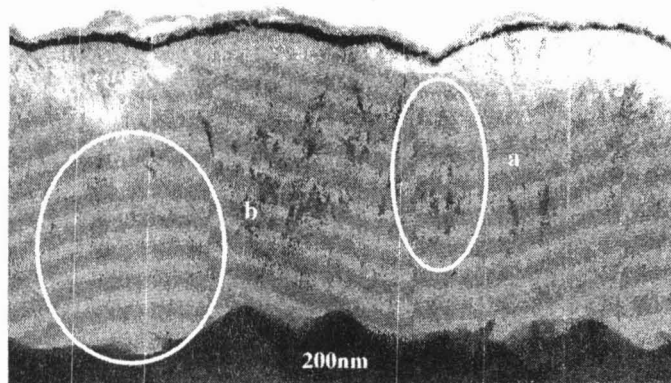


Fig. 3: TEM Bright Field Micrograph of the 2.5 μm thick Solar Cells deposited at textured $\lambda=63\text{ nm}$ ZnO/Ag/SnO₂/glass substrate. (a) Void and Cracks appear brighter and (b) Indicated Growth Collision near textured substrate

As already mentioned above, perpendicular carrier transport has a quit large contribution on the device operation, and the change of the (220) preferential orientated poly-Si films strongly to have influence on the carrier transport, the low μ_a for electron transport and high μ_a for hole transport in the high textured substrate (Figure 1 (d)), be inside that the films exhibit n-type character, also the microstructure films tends becomes random orientation and exhibit poor quality in term of the short carrier lifetime

Conclusion

AC-conductivity measurements have been performed for evaluating the electrical conductivities along the poly-Si growth deposited on the substrate with different surface texture. The poly-Si deposited on highly textured substrate ($\lambda > 37\text{ nm}$) exhibits n-type character, yielding poor photovoltaic performances.

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