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The effects of orientation changes in indium tin oxide films on performance of crystalline silicon solar cell with shallow-emitter

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ABSTRACT

In this study, a cost effective and low temperature approach to fabricate a shallow-emitter crystalline silicon (c-Si) solar cell using a low sheet resistance, and highly transparent indium tin oxide (ITO) as an antireflection layer is presented. Deposited films with either (400) or (222) predominant planes were obtained by varying the substrate temperature. Better crystallization, good electrical properties, higher optical gap, and higher work function were observed for the films with (400) predominant planes; however, the transmittance in the near-infrared region suffered from free-carrier absorption effect. These ITO films were applied to replace the conventional SiN_x film, as an antireflection coating for a c-Si solar cell with shallow-emitter having a sheet resistance of 100 Ω/□. Using the optimal condition, the photovoltaic parameter of the device yielded an open-circuit voltage and fill factor of up to 604 mV and 81.59%, respectively, resulting in an efficiency of 17.27%. This photovoltaic conversion efficiency, based on the c-Si solar cell with shallow-emitter, is relatively higher than that of the current reports.

1. Introduction

The crystalline silicon (c-Si) solar cell market, at a share of about 90%, has been decelerated for mass deployment due to the cost burden [1,2]. Solar cell cost-effectiveness could be obtained by enhancing the conversion efficiency and/or by developing a new method to reduce the process cost [3,4]. A potential for low process cost using a metal–insulator–semiconductor or Schottky type solar cells have been intensively investigated. However, these types of cells undergo a reduction of photocurrent due to the metal shading loss or decrease in the absorbed region [1,5,6]. Another practical approach to reduce the process cost is to control the emitter doping profiles [7]. By using a heavily doped emitter, the contact properties between the metal and semiconductor could be improved, resulting in improved fill factor (FF). However, the short-circuit current density (J_{sc}) is degraded because of high front-surface recombination which causes the blue response loss. In contrast, while shallow-emitters may overcome the problematic recombination, the sheet resistance increases, leading to degradation of the FF and cell efficiency (η) [1].

It is reported that indium tin oxide (ITO) films could be considered as a practical solution to the problem of high resistivity in shallow-emitter solar cells, replacing the conventional SiN_x films [1,8,9]. The internal resistance of a completely fabricated solar cell can be effectively reduced by application of the ITO coating over the existing metal contact structure of the front surface of the cell [8]. In addition, ITO films show excellent optical transmittance and are relatively stable at the high temperature required for solar cell processes [1]. Despite the several investigations carried out based on ITO antireflection for shallow-emitter solar cells [1,8,9], their low efficiencies still present a challenge that needs to be overcome.

In this paper, we report the dependency of ITO film properties and performance of related shallow-emitter silicon solar cells on the ITO plane as it changes from a normally occurring (222) plane to a (400) plane. The results show that the photovoltaic conversion efficiency is higher than that of the currently reported results [1,8,9].

2. Experimental details

ITO films were deposited from an ITO target containing 90 wt% of In_2O_3 and 10 wt% of SnO_2 using the radio frequency (rf)-magnetron sputtering technique. Corning Eagle 2000 glass was

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used as the substrates. The substrates were thoroughly cleaned in acetone, isopropyl alcohol and de-ionized water baths, in that order. The chamber of the sputtering unit was evacuated until the initial pressure of 1.333×10^{-4} Pa before admitting argon (99.999% purity) at a pressure of 2.66×10^{-1} Pa. Pre-sputtering was conducted for 10 min to gain stability and to remove impurities while the substrates were prevented from being exposed to the target by using a shutter. During the deposition process, the rf-power was kept constant at 685 mW/cm^2, while the substrate temperature was varied from 200 to 350 °C in order to change the X-ray diffraction (XRD) peaks and, $I_{(222)}/[I_{(222)}+I_{(400)}]$ ratios. For the fabrication of shallow-emitter based c-Si solar cells, solar-grade thin Czochralski-Si wafers with crystal orientation of (100), resistivity of 1.5–2 Ω cm and thickness of ~200 μm were used as the starting material. A pyramidal surface was formed by conventional alkali texturing. A shallow n^+-emitter with a sheet resistance of 100 Ω/□ was constructed on the top of the textured wafer by phosphorus diffusion in a closed tube furnace. Rear side metallization was formed with standard aluminum paste by screen-printing. The ITO was coated on the top of the cell as an anti-reflection coating (ARC). The front grid-contacts were formed by silver paste screen printing followed by a firing step at 150 °C for metallization in a belt furnace. The active area of the solar cell was 5.2×5.2 cm^2.

The thickness of the ITO films were measured using ellipsometry (SE MF-1000), and the average value was found to be 100 ± 5 nm. The optical transmittance and optical reflectance were measured in the wavelength range of 300–1100 nm using a UV–vis spectrophotometer. The resistivity (ρ), carrier concentration (n) and Hall mobility (μ) of the films were measured at room temperature using the Hall Effect measurement based on the van der Pauw geometry. The structural properties of ITO films were analyzed using XRD (Panalytical PW 3060) with Cu$K\alpha$ radiation (λ=0.1541 nm) in the scan range of 2θ between 15° to 90°. An X-ray photoelectron spectroscopy (XPS) system with a monochromatic Al$K\alpha$ (1486.6 eV) was used to measure the work-function (Φ) and the chemical composition of the ITO films. The quantum efficiency (QE) of the solar cells was measured using the solar cell spectral measurement system (QEX7). The solar cell performance was characterized by current–voltage measurements at room temperature under dark and illuminated (AM1.5 and 100 mW/cm^2) at 25 °C conditions. The equilibrium band diagram of the front interface of a solar cell was studied using automat for the simulation of heterostructures simulated software [10].

3. Results and discussion

In Fig. 1(a), the relative peak intensity of the (222) plane or $I_{(222)}/(I_{(222)}+I_{(400)})$ is shown as a function of the substrate temperature. The peak intensities, $I_{(222)}$ and $I_{(400)}$, were extracted from the XRD results. It can be seen that the relative peak intensity of the (222) plane or the $I_{(222)}/(I_{(222)}+I_{(400)})$ decreases with increasing substrate temperature. The formation of the (400) plane becomes more dominant with higher deposition temperature. It is well known that the degree of the (400) plane is expected to be dependent on the mobility of the adatoms on the substrate [11]. In addtion, the mobility of the adatoms would be proportional to the diffusivity of adatoms on the surface of the film, which can be expressed as the following equation [11,12].

$$\Lambda = 2(Dt)^{1/2} = \nu_{os}^{1/2} a (e^{-E_s/kT})^{1/2} \quad (1)$$

where D is the diffusivity or diffusion coefficient of the adatoms on the substrate of the films, ν_{os} is the vibrational frequency of adatoms, a is the atomic dimension and E_s is the reaction activation energy of surface diffusion. k and T are the Boltzmann's constant and substrate temperature, respectively. Substrate temperature can be a direct influence for adatom mobility. At high substrate temperature, the adatoms have sufficient activation energy for generating the nuclei of the (4 0 0) plane. This clearly shows that the relative peak intensity of the (4 0 0) plane increased as the deposition temperature increased.

To explain the reason for the Φ_{ITO} increase with respect to the formation of the (400) plane, as shown in Fig. 1(a), narrow scan XPS spectra of the O_{1s}, In3d ($In3d_{3/2}$ and $In3d_{5/2}$) and Sn3d ($Sn3d_{5/2}$ and $Sn3d_{3/2}$) was investigated and is shown in Fig. 1(b)–(d). The peaks at 530.0, 493.0, 486.0, 444.0 eV and 452.0 eV correspond to O_{1s}, $Sn3d_{3/2}$, $Sn3d_{5/2}$, $In3d_{3/2}$ and $In3d_{5/2}$, respectively. The Shirley type base line with mixed Gaussian and Lorentzian profiles was utilized to fit the XPS curve [13]. In Fig. 1(b), two different components were found at the binding energies of 530.4 and 531.3 eV. The first peak was due to the lattice oxygen in the crystalline indium-tin oxide and the second peak to the oxygen in an amorphous ITO phase [14]. The best fitting was also obtained with two components at the binding energies of 444.70 and 445.28 eV for $In3d_{5/2}$ and 452.28, and 453.02 eV for $In3d_{3/2}$, where the peaks at 444.08 and, 445.28 eV were assigned to crystalline Indiumm oxide (In_2O_3) and amorphous In_2O_3, respectively. From the fitting data, the percentages of In, Sn and O in the deposited ITO films as a function of the $I_{(222)}/(I_{(222)}+I_{(400)})$ are listed in Table 1. With the formation of the (400) plane, the In and Sn percentages reduce while the total O percentage increases. It can also be seen that the atomic percentage of the surface oxygen corresponding to the crystalline ITO increases with the formation of the (400) plane. Based on the XPS results, it is concluded that when the formation of the (400) plane becomes more dominant, the Φ_{ITO} increases not only with a decrease in the amount of In and Sn in the films, but also with an increase in the amount of the crystalline ITO phase with respect to that of the amorphous phase. These results are consistent with those obtained by Ishida et al. [14].

Fig. 2(a) shows the resistivities, the Hall mobilities and the carrier concentrations of the ITO films as a function of the $I_{(222)}/(I_{(222)}+I_{(400)})$ ratios. It is observed that the film deposited with the (400) preferred plane has better electrical properties than the (222) films. The comparison of the observed structural and electrical properties reveals that in our films, the change in carrier concentration, Hall mobility and conductivity could be attributed not only to the ionized impurity scattering centres, but also to the oxygen content. Lower oxidation and/or higher ionized impurity results in better crystallization and electrical conductivity, carrier concentration and Hall mobility.

The optical properties of the films, such as optical-band gap and optical transmittance spectra were also determined and are shown in Fig. 2(b). The transmission spectra exhibit mostly higher transmittance in the visible wavelength region with the formation of the (400) plane. The increase in visible transmittance can be ascribed to the improvement of the structural homogeneity and crystallinity [15]. A shift in the absorption edge to a shorter wavelength with the formation of the (400) plane, which means band gap widening, is attributed to the Burstein–Moss (B–M) effect. In the infrared region, the optical transmittance is lower for the formation of the (400) plane. This lower optical transmittance can be attributed to the free-carrier absorption (FCA) effect as reported previously [16]. Therefore, in the formation of the (400) plane, the higher optical transmittance was obtained in the visible and shorter wavelength region, while in the infrared region the optical transmittance behavior is lower. Our results contrast those of Thilakan et al. [17], who indicated that the optical transmittance of the (400) oriented films was comparatively less in all wavelength regions.

Fig. 3(a) depicts the schematic structure of the shallow-emitter c-Si solar cell fabrication, on which ITO film having plane changing from the nomally occuring (222) plane to the (400) plane. The current density versus the voltage plots for the devices in Fig. 3 (a) was shown in Fig. 3(b). All cell parameters were noticeably varied with respect to the formation of the (400) plane of the films. The highest J_{sc} of 35.52 mA/cm^2 was obtained with the $I_{(222)}/$