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Role of double ITO/In_2O_3 layer for high efficiency amorphous/crystalline silicon heterojunction solar cells

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ABSTRACT

The high work function transparent conductive oxide films can be use to modify the front barrier height of amorphous/crystalline silicon heterojunction solar cells. We report the implementation of double ITO/In_2O_3 films as a front anti-reflection electrode in amorphous/crystalline silicon heterojunction solar cells. The In_2O_3 and ITO films were deposited by in-situ radio frequency (RF) magnetron sputtering system. The thin In_2O_3 films were used to modify the front contact barrier height of amorphous/crystalline silicon heterojunction solar cell due to their high work function while the ITO films were used to improve the conductivity of front transparent conductive oxide layer. We investigated the electrical and optical properties of double ITO/In_2O_3 layer with the variation of film thickness. In order to satisfy the requirement of solar cell applications, the optimum combination of thickness in terms of sheet resistance, resistivity, transmittance, etc. was sought. The double ITO/In_2O_3 layer with the thickness of 80/20 nm were applied as front anti-reflection electrode and the best performance of the device was found to be; V_{oc} = 670 mV, J_{sc} = 37.42 mA/cm^2, FF = 71.16% and η = 17.84%.

1. Introduction

The heterojunction with intrinsic thin layer (HIT) solar cell has attracted interests as novel photovoltaic device due to the high efficiency. There are many factors that limit the performance of HIT solar cell. One of the factors is the work function of transparent conductive oxide (TCO) films that produces the band bending effect in TCO/a-Si:H(p) interface. An electron injection barrier is developed due to the difference in work function of TCO and a-Si:H (p) layer which limits the flow of hole carriers from a-Si:H(p) to TCO layer. Therefore the high work function TCO films are preferred to decrease the band offset of TCO/a-Si:H(p) interface in HIT solar cells [1–3].

The ITO films are commonly used as an anti-reflection layer due to their low resistivity, high transmittance in visible wavelength region and wide optical band gap for flat panel displays and solar cells [4,5]. There are certain applications like large area flat panel displays and heterojunction solar cells require further improvements in optical and surface properties of the ITO films. The work function of ITO films can be modified by substrate temperature and reactive sputtering as reported by several studies [2,6–8]. During the enhancement of work function, few of electrical and optical properties of ITO films are needed to sacrifice. In this study, we propose a double ITO/In_2O_3 layer to increase the work function without scarifying the conductivity and transmittance. The high work function hydrogenated In_2O_3 films reduces the band offset of TCO/a-Si:H(p) interface while the ITO films provide good electrical and optical properties [9,10]. Although there have been several reports on the enhancement of ITO work function, the influence of double ITO/In_2O_3 layer on the barrier height modification and performance of HIT solar cells is yet to be reported.

In this article, we report the influence of double ITO/In_2O_3 layer on the TCO/a-Si:H(p) interface and performance of HIT solar cell. The electrical, optical, structural and surface properties of the double ITO/In_2O_3 layer are described. The performance and quantum efficiency of HIT solar cell for various film thicknesses of double layer is investigated. The precise role of double ITO/In_2O_3 layer on the band diagram of HIT solar cell is also discussed.

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2. Experimental details

The ITO/IO:H film were deposited on (2.5 × 2.5) glass substrate by RF-magnetron sputter system with in-situ deposition method with multi sputter guns. The total thickness of double TCO layer was fixed to be 100 nm for each sample. Initially, front ITO films were deposited for the thickness of 20–100 nm and then the samples were rotated onto the In_2O_3 target to deposit with the thickness of 100–20 nm in rapid succession. The indium tin oxide films were deposited from the ITO target that was composed of 90 wt% In_2O_3 and 10 wt% SnO_2 with 99.999% purity. The hydrogenated indium oxide (IO:H) films were deposited from 99.999% purity of In_2O_3 target with the gas phase hydrogen reactive sputtering (Ar + H_2). The substrate temperature and the RF power density were kept constant at room temperature (RT) and 0.9 Wcm^{-2}, using turbo molecule pump. The chamber of sputtering unit was evacuate to the pressure of 5×10^{-7} Torr before injecting Ar + H_2 (99.999% purity) at a working pressure of 2×10^{-3} Torr exactly. Fig. 1 depicts the schematic structure of the HIT solar cell on which double ITO/In_2O_3 layer was applied. The commercial *n*-type solar graded Si wafer (100 Ω cm, 300 μm thick, (100) oriented) was used as base material. The wafers were cleaned by RCA 1 (H_2O_2–NH_4OH–H_2O) and RCA 2 (H_2O_2–HCl–H_2O) processes after an ultrasonic treatment. The a-Si:H(p/i) layers were deposited on the front-side of the Si wafer at 200 °C by plasma-enhanced chemical vapor deposition (PE-CVD) process. The PE-CVD system was used to deposit the a-Si:H(i/n) layers on the rear side of Si wafer at 200 °C. The Ag (~0.1 μm)/Al (1 μm) and Al (1 μm) electrodes were formed on the ITO and back surfaces by thermal evaporation for good ohmic contacts.

The thickness of ITO and IO:H films was measured by spectroscopic ellipsometry (HR-190) at room temperature. The electrical properties such as resistivity, carrier concentration and Hall mobility were measured for TCO samples with defined area of 15 mm × 15 mm by Hall effect measurement (Ecopia HMS-3000) system at room temperature. The optical properties such as transmittance and reflectance were characterized by UV–vis spectrophotometer (Scinco S-3100). The high resolution scanning electron microscopic (HR-SEM) system was used to examine the surface morphology of ITO/In_2O_3 films. The growth peak intensities were measured by X-ray diffraction (XRD) to analyze the crystallinity of double TCO layer with various thicknesses. The solar cell performance was characterized by current density–voltage (*J*–*V*) measurements under dark (temperature range of 298–398 K) and illumination (AM1.5 and 100 mW/cm^2) at room temperature (25 °C) conditions. The quantum efficiency (QE) of HIT solar cells was characterized by solar cell spectral response/QE/IPCE measurement system QEX7.

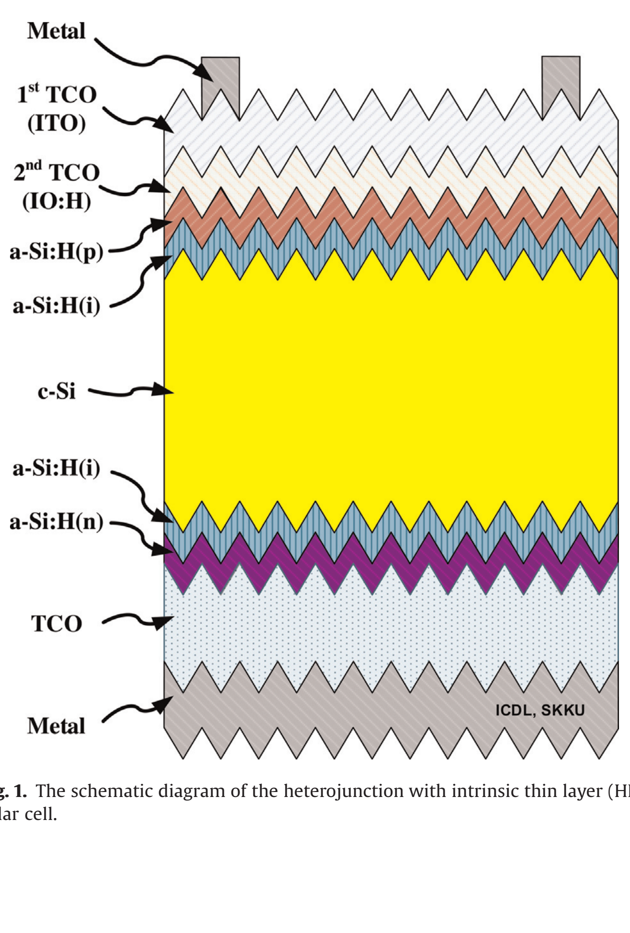

Fig. 1. The schematic diagram of the heterojunction with intrinsic thin layer (HIT) solar cell.

3. Results and discussion

Fig. 2 shows the electrical characteristics such as resistivity, sheet resistance, carrier concentration and mobility of double ITO/In_2O_3 layer as a function of film thickness. The double ITO/In_2O_3 layer showed the lowest resistivity of 1.72×10^{-4} Ω cm for the ITO film thickness of 100 nm. Since the ITO films have higher electrical conductivity than In_2O_3 films, the resistivity of double layer increased from 1.72×10^{-4} to 7.4×10^{-4} Ω cm with the variation of ITO/In_2O_3 film thickness from 100/0 to 0/100 nm. The sheet resistance of double ITO/In_2O_3 layer was also increased from 17.2 to 74 Ω/□ for the film thickness from 100/0 to 0/100 nm [9,11,14,15]. The carrier concentration of double ITO/In_2O_3 layer was decreased from 11.6×10^{20} to 2.82×10^{20} cm^{-3}. Since the sheet resistance is closely related with fill factor of HIT solar cell, it should be less than 40 Ω/□ for the application of HIT cells. Three samples with different combination of layer thickness were applied to the HIT cell fabrication.

The optical transmittance of double ITO/In_2O_3 layer is shown in Fig. 3 for various film thicknesses. The double ITO/In_2O_3 layer with the film thickness of 80/20 nm showed higher transmittance than single ITO layer in the wavelength region from 450 to 700 nm and from 900 to 1100 nm. Only the absorbable wavelength region was considered because the energy bandgap of crystalline silicon is 1.1 eV. As the In_2O_3 film gets thicker, the peak position around 300 nm shifts toward longer wavelength region. Pure In_2O_3 layer has only one peak in the longer wavelength region. Increasing the In_2O_3 film thickness was not preferable for the solar cell application as the sample with thick In_2O_3 layer shows low transmittance in the wavelength region between 650 nm and 1100 nm. It was noted that the double ITO/In_2O_3 layer with the

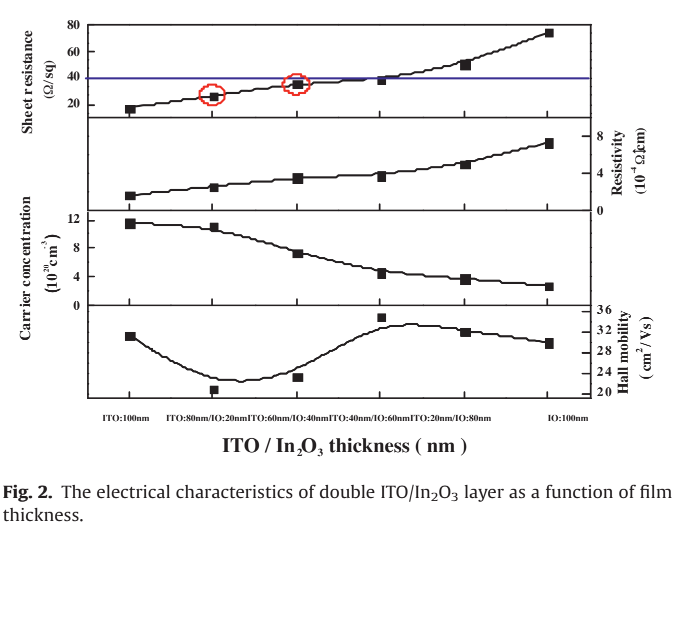

Fig. 2. The electrical characteristics of double ITO/In_2O_3 layer as a function of film thickness.