



Development of highly conducting n-type micro-crystalline silicon oxide thin film and its application in high efficiency amorphous silicon solar cell



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ABSTRACT

Wide band gap and highly conducting n-type nano-crystalline silicon film can have multiple roles in thin film solar cell. We prepared phosphorus doped micro-crystalline silicon oxide films (n- $\mu\text{c-SiO:H}$) of varying crystalline volume fraction (X_c) and applied some of the selected films in device fabrication, so that it plays the roles of n-layer and back reflector in p-i-n type solar cells. It is generally understood that a higher hydrogen dilution is needed to prepare micro-crystalline silicon, but in case of the n- $\mu\text{c-SiO:H}$ an optimized hydrogen dilution was found suitable for higher X_c . Observed X_c of these films mostly decreased with increased plasma power (for pressure < 2.0 Torr), increased gas pressure, flow rate of oxygen source gas and flow rates of $\text{PH}_3 > 0.08$ sccm. In order to determine deposition conditions for optimized opto-electronic and structural characteristics of the n- $\mu\text{c-SiO:H}$ film, the gas flow rates, plasma power, deposition pressure and substrate temperature were varied. In these films, the X_c , dark conductivity (σ_d) and activation energy (E_d) remained within the range of 0–50%, 3.5×10^{-10} S/cm to 9.1 S/cm and 0.71 eV to 0.02 eV, respectively. Low power (30 W) and optimized flow rates of H_2 (500 sccm), CO_2 (5 sccm), PH_3 (0.08 sccm) showed the best properties of the n- $\mu\text{c-SiO:H}$ layers and an improved performance of a solar cell. The photovoltaic parameters of one of the cells were as follows, open circuit voltage (V_{oc}), short circuit current density (J_{sc}), fill-factor (FF), and photovoltaic conversion efficiency (η) were 950 mV, 15 mA/cm², 64.5% and 9.2% respectively.

1. Introduction

Hydrogenated silicon oxide alloy is one of the most popular materials for solar cell, because of its widely tunable optical gap and two phase material structure [1,2]. Such a material can have useful applications in thin film amorphous silicon (a-Si:H) solar cell. A single junction a-Si:H solar cell have various limitations, like significant parasitic optical absorption in the doped layers, imperfect p/i and i/n interfaces, lower conductivity of doped layer, limited spectral band width of optical absorption of intrinsic a-Si:H films and limited light trapping within the cell are few of them. Although continuous research and development have been going on and significant progress is made in these areas but the overall efficiency of a single junction cell remains mostly around 10%. In a multi junction or tandem cell structure, the roles of generating photo carriers are distributed among the component cells. In these devices optically transparent p-type and n-type layers with high electrical conductivity are preferable [3,4]. In a solar cell light has to pass through the doped layers before it enters active layer,

where the electron-hole (e-h) pairs are generated for photo-voltaic energy conversion. A suitably prepared silicon oxide layer can have high transparency [5]. An n-type silicon oxide layer can also act as an intermediate reflector in a tandem cell structure [5–13] or back reflector [12–14], window layer [14] etc, that can help in light trapping. Usually an optically transparent zinc oxide (ZnO) is used as a back reflector layer. However, a highly transparent and electrically conducting n-type silicon oxide layer may play dual roles as n-type layer and a replacement of the ZnO as back reflector [15,16].

Improving electrical conductivity of p-layer and p/i interface are other aspects where improvements were reported. In a light trapping scheme and multi junction device structure, the light that passes through the n-type layer are used for further carrier generation. Therefore optical transparency of the n-type layer becomes important.

Intrinsic and doped types of this oxide material were investigated extensively and reported in the past. The primary role of the doped layer in a thin film p-i-n type solar cell is to create the necessary internal electric field, so that photo-generated e-h pairs are separated and

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delivered to the outer circuit. However, these layers inevitably act as parasitic optical absorbers for the incident light. In a multi junction or tandem cell structure, the situation is even more severe as multiple cells are series connected along the light path, and each cell must have at least two such doped layers. Thereby, the available light for the active layer may remain significantly low with low band gap doped layers. A possible solution to this situation is to use wider optical gap or transparent highly conducting doped layers. The silicon oxide can be prepared as a wide band gap material, so it has the potential to be one such suitable material and n-type micro-crystalline silicon oxide (n- μ c-SiO:H) may become a better alternative to the widely used n- μ c-Si:H [17].

Several investigations were reported on the preparation and properties of amorphous and micro-crystalline silicon oxide materials, both of undoped and doped type. These results indicate that the presence of oxygen influences preparation of a micro-crystalline silicon oxide (μ c-SiO:H). It was proposed that the two phase structure of the silicon oxide material can be useful in obtaining high optical gap as well as high electrical conductivity. The Si-rich part of the material can provide higher conductivity while the oxygen rich Si-O-Si phase of the material can help widening its optical gap [1,2].

We investigated and optimized the preparation of n- μ c-SiO:H material with a clear understanding of the roles of various deposition parameters and therefore we are able to improve the n-type material. Afterwards this material was applied in a solar cell as n-type layer with its additional role as a back reflector.

2. Experimental

The n- μ c-SiO:H layers and solar cells were deposited in a cluster type multi chamber plasma enhanced chemical vapor deposition (PECVD) system. Silane (SiH_4), hydrogen (H_2) was the common source gases for all the p-type, i-type and n-type layers of the cells. Additional carbon dioxide (CO_2) and diborane (B_2H_6) was used for preparing p-type silicon oxide layers, while CO_2 and phosphine (PH_3) was used for preparing n-type layer of the solar cells. Some of the reported results can be found elsewhere [4,18–22]. Initially the individual n-type layers were deposited on clean glass substrates, characterized and optimum deposition conditions were determined. Phosphine, hydrogen and carbon dioxide gas flow rates were varied from 0.05 to 0.20 sccm, 300 to 1000 sccm and 1 to 20 sccm respectively. Furthermore, the radio frequency (RF) plasma power pressure and substrate temperature (T_s) were varied within 20 W to 200 W, 1.5 Torr to 2.5 Torr, and 110 °C to 250 °C respectively. In all the n- μ c-SiO:H film depositions, the SiH_4 gas flow rate was kept constant at 3 sccm, and the electrode separation of the PECVD system was kept at 20 mm.

The optical absorption, electrical dark conductivity (σ_d), activation energy (E_a) and Raman spectral analysis were carried out on these films. The optical properties were estimated from the spectroscopic ellipsometric analysis (V-VASE series, J.A. Woollam). The optical gap of the films was estimated as the photon energy at which the absorption coefficient is 10^4 cm^{-1} , denoted as E_{O4} . We used the E_{O4} method of measuring the optical gap as it is a simple and a relatively less error prone technique in comparison to the Tauc's method. However, if the Tauc's gap of the films were carefully estimated then a linear relation can easily be found between the E_{O4} and the Tauc gap [23]. Therefore, as the E_{O4} and the Tauc gap seems to be related and the E_{O4} simpler to estimate, we used this technique.

Planar aluminum (Al) metal electrodes were vapor deposited on the individual film surfaces for measuring transverse electrical conductivities at various temperatures. Here Al electrodes were deposited on the n- μ c-SiO:H layer by physical vapor deposition under vacuum. It is known by Arrhenius relation (1), that the temperature dependent dark conductivity (σ_d) is material specific, where the material specific parameter is the activation energy (E_{act}). The σ_d can be directly measured but the E_{act} were estimated by using the Arrhenius relation

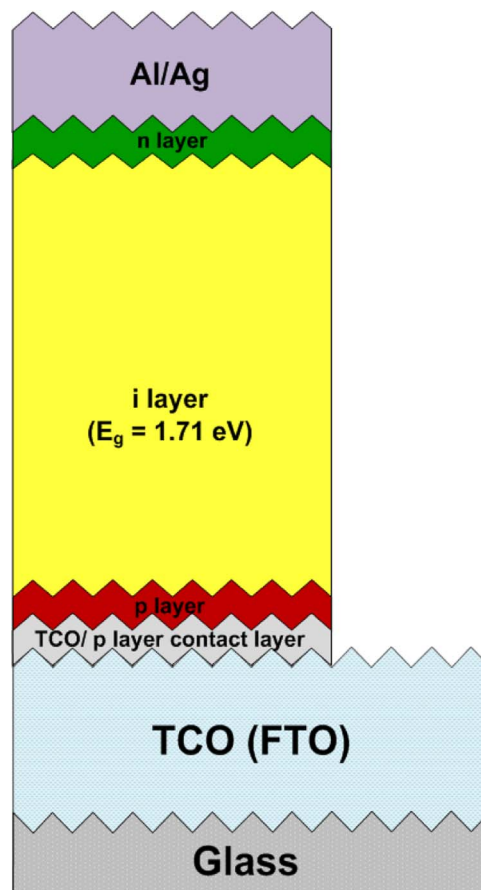


Fig. 1. Schematic diagram of single junction p-i-n type solar cell.

(1) in a graphical plot,

$$\sigma_d = \sigma_0 \exp[-E_{act}/kT] \quad (1)$$

here σ_0 is a constant, T temperature in Kelvin and k is Boltzmann constant.

Raman spectra of the n-layers was used to estimate the crystallite volume fraction (X_c) within the films, where the X_c 's were estimated from the peak intensities at 520 cm^{-1} (I_{520}), 500 cm^{-1} (I_{500}) and 480 cm^{-1} (I_{480}) by using the relation (2).

$$X_c = (I_{520} + I_{500}) / (I_{520} + I_{500} + I_{480}) \quad (2)$$

The efficiency of the solar cells (η) were estimated after extracting the V_{oc} , J_{sc} , FF parameters from the J-V characteristic curve under AM1.5 G insolation, and following the relation, $\eta = V_{oc} \cdot J_{sc} \cdot FF$, here FF is fill factor.

The p-i-n type cells were fabricated on fluorine doped tin oxide (FTO) coated glass (Asahi VU glass). Fig. 1 shows a schematic diagram of such a solar cell, where various n-layers was as applied at the back of the device. Before deposition of the first p-type layer, a 20 nm thick Al doped ZnO layer was sputter deposited on the FTO surface. The cells were characterized by measuring current density-voltage (J-V) characteristic curves under standard AM1.5 insolation. From the J-V characteristic curves the photovoltaic parameters like open circuit voltage (V_{oc}), short circuit current density (J_{sc}), fill factor (FF), and efficiency (η) were estimated. External quantum efficiency (EQE) of the devices were measured using QEX7 model system of PV Measurement Inc. Different solar cells were fabricated by varying the n-layer.

3. Results and discussions

In order to determine optimum deposition conditions for the n- μ c-SiO:H film, almost all the deposition parameters were varied except the

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