PROPERTIES OF TiO2 LAYERS AS ANTIREFLECTION COATING FOR AMORPHOUS SILICON BASED THIN-FILM SOLAR CELLS

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ABSTRACT: This study focuses on an optimized light incoupling into silicon thin-film solar cells by refractive-index matching. We applied a titanium dioxide (TiO2) interlayer between front contact and silicon. The TiO2 thin-film deposition process has to be adjusted carefully to realize a transparent and sufficiently conductive film for the device application. The TiO2 layers were deposited using rf-magnetron sputtering of doped and undoped TiO2 targets. The influence of doping concentration, substrate temperature and oxygen content in the sputtering gas phase on the TiO2 properties have been studied. The TiO2 layers are characterized electrically and optically whereas the light managing performance is verified by application in microcrystalline silicon thin-film solar cells. A considerable improvement in short-circuit current by 0.8 mA/cm² has been demonstrated.

Keywords: TiO2, Antireflection Coating, Sputtering

1 INTRODUCTION

Silicon thin-film solar cells are promising candidates for photovoltaic power generation in future. One approach employs hydrogenated amorphous silicon (a-Si:H) based active layers in single- or multi-junction solar cells. In p-i-n configuration the cell is illuminated through transparent conductive oxide (TCO) when a superstrate (viz. glass) device configuration is used. Due to the intrinsically low absorbance of silicon in the long wavelength range, photon management is essential. The photon management comprises efficient coupling of light into the device as well as light trapping within the device. In general, the light trapping is achieved by combining front contact TCO with optimized properties as well as highly reflective back contacts. Besides being transparent and conductive, the TCO has to scatter the light efficiently. This is an important way to enhance light trapping inside the p-i-n device. However, there are still significant losses due to direct reflection of the light from the interface between TCO and silicon due to mismatch of refractive index.

In this paper, we want to focus on an optimized light coupling into the device which can be realized by refractive-index matching. The refractive index of titanium dioxide (TiO2) has a value intermediate of that of ZnO and silicon. It has already been shown experimentally that a thin interlayer of TiO2 between ZnO and silicon works as an antireflection layer [1]. The TiO2 thin-film deposition process has to be adjusted carefully to realize a transparent and sufficiently conductive film for the device application. In optimization of the properties of TiO2, the complicated interrelation with the film to silicon deposition environment has to be considered. A chemical reduction of TiO2, which happens during the exposure to hydrogen plasma in PECVD deposition of microcrystalline silicon (µc-Si:H), leads to additional absorption losses. This can be prevented by a thin coating with plasma-resistant ZnO on top of TiO2 layer. Thus TiO2/ZnO bilayers are used as antireflection structure between TCO front contact and silicon [1]. The individual thicknesses have to be adjusted carefully to optimize the absorption loss.

2 EXPERIMENTAL

The TiO2 thin films have been deposited on Corning 1737 glass with substrate size of 10x10 cm² by rf-magnetron sputtering of undoped: TiO2 and doped: TiO2:Nb2O5 targets with 99:1 wt.% and 95:5 wt.%. The sputtering gas was pure argon gas or a mixture of argon and oxygen. The concentration of oxygen is set as a variable parameter in this study. The substrate temperature was varied in a range of room temperature (RT) to 500 °C. The Substrate temperature was calibrated by a thermal sensor and was controlled by the heater temperature. The deposition pressure was kept constant at 0.3 Pa. The TiO2 thin films have been characterized electrically (conductivity measurement) and optically (absorption by UV-VIS-NIR spectrometry). The light enhancement performance is verified by application in thin-film silicon solar cells. For this purpose the TiO2 layers are deposited onto rf-magnetron sputtered aluminum-doped zinc oxide (ZnO:Al) that had been surface-textured by wet-chemical etching with diluted hydrochloric acid (0.5% HCl) [2,3]. The TiO2 layer was covered with an additional 10 nm thick zinc oxide layer for protection against hydrogen plasma treatment during silicon deposition [1]. The silicon layers were prepared using plasma-enhanced chemical vapor deposition (PECVD) at 13.56 MHz excitation frequency in a 30x30 cm² reactor. The details of this process, the PECVD system and cell preparation are described elsewhere [4,5]. Double layers of sputter-deposited ZnO:Al (80 nm) and thermally evaporated silver (700 nm) served as back reflector and rear-side contact. The external quantum efficiency (QE) of the solar cells was calculated from spectral response measured at zero bias. The integrated short-circuit current density was derived from convolution of QE data and the AM 1.5 solar spectrum.

3 RESULTS AND DISCUSSIONS

3.1 Effect of substrate temperature

The substrate temperature in sputtering of TiO2 thin films has been varied from room temperature (25 °C) to 500 °C. The conductivity of TiO2 thin films changes significantly with variation of substrate temperature. Fig. 1 shows the conductivity of TiO2 thin films against substrate temperature using both the undoped target
(open squares) and the two doped target (green circles and red triangles). Pure argon was used as deposition gas for all thin films shown in Fig. 1. All sets of thin films show the tendency of increasing conductivity with increasing substrate temperature up to about 300 °C. While in case of the undoped target and the 1wt.% doped target the increase in conductivity with substrate temperature shows a linear tendency up to about 500°C (a fit is drawn as guide to the eye), the 5wt.% doped target shows maximized conductivity values in the range of about 150 °C to 300 °C. So far, the highest conductivities have been found by employing the undoped target.

Fig. 1: Conductivity of TiO₂ against substrate temperature $T_S$ during sputtering. Pure argon gas was used for sputtering.

Besides conductivity, achieving a high transparency is very crucial from applications point of view. The absorption of the TiO₂ thin films has been calculated using the transmission and reflection spectrometer measurements. Fig. 2 shows spectrally dependent absorptions of some of the TiO₂ films sputtered using the doped target and using pure argon as deposition gas. Due to a measurement artifact around $\lambda = 900$ nm there is no data in this spectral range. All layers shown had a thickness in the range of 250 nm to 290 nm. The trend is the increase in absorption with increase in the substrate temperature.

Thus, combining results of Fig. 1 and 2, with increasing substrate temperature the TiO₂ layers become more conductive and less transparent, and an optimized deposition regime is essential to point out for device application.

3.2 Effect of oxygen concentration in argon

The effect of concentration of O₂ in Ar in gas phase during the deposition of TiO₂ thin films has been studied. Fig. 3 shows the conductivity of the films against the oxygen content for the TiO₂ thin films sputtered using the undoped target (open squares) and the doped target (green circles and red triangles). In case of the 1wt.% doped TiO₂ target and pure argon gas, a variation in conductivity by four orders of magnitude is observed (compare Fig. 1).

Fig. 3: Conductivity against oxygen content of sputter gas.

Adding a small amount of oxygen (~0.1%) to the deposition gas decreases the conductivity by two to six orders of magnitude. The conductivity decreases with incorporation of more O₂ in the gas phase. In case of TiO₂ thin films sputtered using the undoped target a similar trend is observed, even though few layers with pure argon deposition gas show low conductivity as well as few layers with small concentration of oxygen in the deposition gas showed comparable high conductivities.

Fig. 4: Absorption of TiO₂ layers (thickness in the range 40 nm to 75 nm).

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The TiO$_2$ layers sputtered employing the 5wt.% doped target and pure Ar deposition gas show a variation in conductivity by eleven orders of magnitude, as already shown in Fig. 1. Adding small amounts of oxygen to the deposition gas results in low conductivity values for both low substrate temperature and $T_S = 135$ °C. Fig. 4 shows absorption data for a set of TiO$_2$ layers using the 1wt.% doped target and at room temperature. It is very interesting to note that with incorporation of O$_2$ the absorption decrease over the whole spectral range 300 nm to 1100 nm useful for device application. There is a monotonic decrease in the absorption with increase in the O$_2$ concentration in the range used in this experiment. Thus, an optimized deposition regime is also very important in case of device application of TiO$_2$ thin films as antireflection coating combining the conductivity and transparency of the films with respect to O$_2$ concentration in Ar in gas phase during the sputtering process.

3.3 Application in thin-film silicon solar cells

TiO$_2$/ZnO bilayers have been applied into microcrystalline silicon thin-film solar cells with intrinsic silicon layer thickness of about 1.1 µm (compare [1]). Fig 5 shows quantum efficiency data of cells with and without antireflection coating. The TiO$_2$ layer was deposited using the undoped (Fig. 5a) and doped (Fig. 5b) target, respectively. In case of Fig. 5a the total cell absorption $1-R_{cell}$ is shown additionally.

CONCLUSION

The sputter deposited TiO$_2$ thin films have been investigated for an antireflection coating. The optical, electrical and structural properties have been investigated. The effect of substrate temperature and concentration of oxygen in argon in gas phase have been studied. An optimized deposition regime has been found where the conductivity and transparency of the films are suitable for the device application. The TiO$_2$/ZnO bilayers have been applied as antireflection coatings in microcrystalline silicon thin-film solar cells. An increase in quantum efficiency in the range of 400 nm to 850 nm has been found which improves the short-circuit current density of the solar cells by up to 0.8 mA/cm$^2$.

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