Extended Abstracts of the 2010 International Conference on Solid State Devices and Materials, Tokyo, 2010, pp1251-1252

Optimum design of a-Si:H/μc-Si:H tandem thin film solar cells with a low-refractive-index AZO transparent conducting oxide

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1. Introduction

Transparent conducting oxides (TCOs) with a wide bandgap have been widely used for transparent electrodes in optoelectronic device applications, such as light emitting diodes, flat panel displays, and thin-film solar cells. Recently, TCO thin films were fabricated by oblique angle deposition (OAD) method to modify the refractive index [1,2]. Especially, for silicon (Si) based thin film solar cells, efficient light trapping is crucial because of their low optical absorption coefficient. In order to improve the efficiency in Si solar cells, it is necessary to employ the antireflective layers which can cover a wavelength range of the solar spectrum. But, it is difficult to optimize experimentally solar cell structures due to the high cost, complexity and time consumption. Numerical modeling and simulation help to optimize the solar cell structure, thus decreasing the time and costs for development. For tandem solar cell structures, the current matching conditions between top and bottom cells should be optimally designed to achieve high conversion efficiency [3].

In this work, we presented the design of a-Si:H/μc-Si:H tandem thin film solar cells with TCO layer of a low-refractive-index (low-*n*) aluminum-doped zinc oxide (ZnO:Al, i.e., AZO), in comparison with the previously reported experimental results, by optimizing the current matching condition between both cells using the Silvaco ATLAS [4].

2. Experiments and Numerical modeling

The AZO thin films on Si (100) and glass (Eagle 2000) substrates were deposited by rf magnetron sputtering system using the OAD method. The ZnO target containing 2 wt.% Al_2O_3 was used. The rf power was 100 W and the film thickness was kept at ~ 500 nm. The AZO thin films were deposited at flux incident angles of $\theta_i = 0^o$ and 80°. The cross-sectional structures of deposited AZO films on Si substrate were observed by using a scanning electron microscope (SEM). Refractive index and extinction coefficient were measured by using a spectroscopic ellipsometer.

The numerical modeling of a-Si:H/μc-Si:H tandem thin film solar cells was verified from the experimentally reported device structure in Ref. [5]. Then, the solar cell structure was optimized to improve the conversion efficiency.

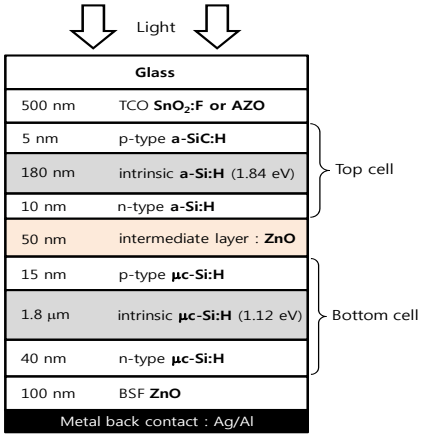

Fig. 1. Schematic diagram of the optimized a-Si:H/μc-Si:H tandem thin film solar cell by current matching between top and bottom cells.

Fig. 1 shows the schematic diagram of the optimized a-Si:H/μc-Si:H tandem thin film solar cell by current matching between top and bottom cells. The intrinsic thicknesses of top a-Si:H and bottom μc-Si:H cells were optimized at 180 nm and 1.8 μm, respectively. For the optimized device structure with TCO layer of fluorine-doped tin oxide (SnO_2:F), the open-circuit voltage (V_{oc}) of 1.39 V, short-circuit current density (J_{sc}) of 12.75 mA/cm^2, and fill factor of 74.1% were obtained under AM1.5g (air mass 1.5 global, 100 mW/cm^2) illumination. The conversion efficiency (η) was increased up to 13.11% compare to that of the Ref. [5].

3. Results and Discussion

Fig. 2 shows the measured refractive index and extinction coefficient spectra of AZO thin films deposited on Si substrate for flux incident angles of $\theta_i = 0^o$ and 80° and SnO_2:F thin films used for the solar cell structures in the wavelength range of 400-1100 nm. The inset shows the cross-sectional view SEM images of the nanocolumnar AZO film at flux incident angles of $\theta_i = 0^o$ and 80°. For $\theta_i = 80^o$, the column inclination angle θ was ~ 30°. The difference between experimental result and theoretical calculation is maybe caused by various effects, i.e. the poor shadow effect, process condition, and flux incident angular distribution. Also, the refractive index of AZO thin film was decreased from 2.05 to 1.96 at 400 nm and from 1.68 to 1.46 at 1100 nm compared to the film deposited at $\theta_i = 0^o$.

The grain boundary of the inclined nanocolumn AZO structure was larger than that of perpendicular structure and the refractive index was lower. This is probably ascribed to the internal reflections and photon energy trapped in the grain boundary. The extinction coefficient also decreased for the inclined AZO nanocolumn structure. However, the extinction coefficient was almost not changed.

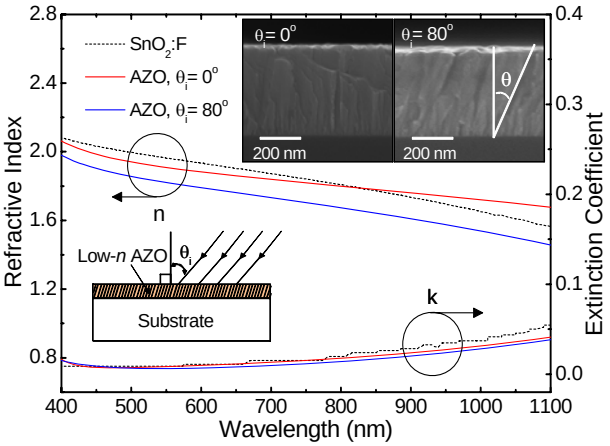

Fig. 2. Measured refractive index and extinction coefficient spectra of AZO thin films deposited on Si substrate for flux incident angles of θ_i = 0°, and 80° and SnO_2:F thin films used for the solar cell structures in the wavelength range of 400-1100 nm.

Fig. 3 shows the I-V characteristics of optimized a-Si:H/μc-Si:H tandem thin film solar cells with different TCO layers. The measured refractive index and extinction coefficient of the nanocolumnar AZO film were used to design the solar cell structure as shown in Fig. 1. For the AZO thin film of θ_i = 80° with lower refractive index than that of θ_i = 0°, a maximum short-circuit current density of J_{sc}= 13.84 mA/cm^2 was obtained, leading to a high conversion efficiency of η= 14.32%. By applying TCO layer with low-*n* AZO to the Si solar cell structure, the conversion efficiency was improved by ~ 1% compare to that of θ_i = 0°. This may be attributed that the low-*n* AZO TCO layer exhibits low refractive index and high transparency. The parameters of optimized a-Si:H/μc-Si:H tandem thin film solar cells with different TCO layers are summarized in Table I.

4. Conclusions

The nanocolumnar AZO thin films were deposited by rf magnetron sputtering system using OAD method. The low refractive index of AZO was obtained at a flux incident angle of θ_i = 80°. The a-Si:H/μc-Si:H tandem thin film solar cell with the TCO layer of SnO_2:F was designed by optimizing the current matching between top and bottom cells. The optimized intrinsic layer thicknesses of top and bottom cells were 180 nm and 1.8 μm, respectively. For the optimized solar cell structure with TCO layer of low-*n* AZO, the conversion efficiency was improved from 13.33% to 14.32% under AM1.5g illumination. This result provides a better understanding of Si based solar cells with low-*n* TCOs, e.g., low-*n* indium-tin oxide (ITO), SnO_2, and ZnO.

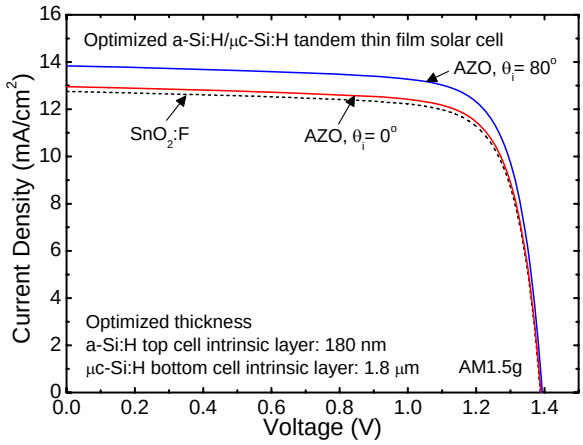

Fig. 3. I-V characteristics of optimized a-Si:H/μc-Si:H tandem thin film solar cells with different TCO layers.

Table I. Parameters of optimized a-Si:H/μc-Si:H tandem thin film solar cells with different TCO layers.

Solar cell(AM1.5g) TCO layer	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	η (%)
SnO_2:F, Ref. [5]	1.37	11.7	74.5	12
SnO_2:F, Optimized	1.39	12.75	74.1	13.11
AZO, θ_i = 0°	1.39	12.96	74.11	13.33
Low-*n* AZO, θ_i = 80°	1.39	13.84	74.24	14.32

Acknowledgements

The work was supported by the Korea Science and Engineering Foundation (KOSEF) grant funded by the Ministry of Education, Science and Technology (MEST) (No. 2010-0016930).

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