**Letter**

**Al₂O₃ antireflection layer between glass and transparent conducting oxide for enhanced light trapping in microcrystalline silicon thin film solar cells**

Dong-Won Kang a, Jang-Yeon Kwon b,*, Jenny Shim c, Heon-Min Lee c, Min-Koo Han a

**1. Introduction**

Silicon thin film solar cells have gained a lot of attention due to their low cost and large-area fabrication potential. Recently, multi-junction structures with different band gaps such as micro-morph tandem cells consisting of an amorphous (a-Si) top cell and a microcrystalline (µc-Si:H) bottom cell have been produced and showed improved efficiency over traditional solar cells [1,2]. In the field of silicon thin film solar cells, light trapping to confine incident light in the photo-active layers is one of the essential technologies needed to decrease silicon thickness and increase device stability against light induced degradation [3,4]. Surface texturing of transparent conducting oxide (TCO) increases optical path lengths, which enhances light absorption [5]. TCO texturing also gives antireflection (AR) properties by refractive index grading. However, a silicon deposition on the highly roughened TCO surface can cause a degradation of other solar cell characteristics due to an increase of shunted current paths in the cells produced [6–8]. To mitigate this problem, insertion of a resistive n-type µc-Si:H interlayer was suggested [9].

The insertion of an additional antireflection layer (ARL) to decrease reflection loss has been investigated. The proposed method does not imply a rougher interface at the TCO/silicon interface, therefore permitting to increase current without the above mentioned problems. In typical thin film solar cells with a superstrate configuration (p–i–n type), incident light is reflected at interfaces between mediums with different refractive indices, such as air/glass, glass/TCO, and TCO/Si before it reaches the silicon layer. In order to decrease those reflection losses, several groups investigated a TiO₂ (n ~ 2.5) ARL to decrease the reflection at the TCO(n ~ 1.9)/Si(n ~ 3.5) interface [3,10,11]. After the ARL was introduced, an efficiency of approximately 11–12% was achieved in micromorph tandem solar cells [3]. However, further increase of the efficiency is needed to enhance the competitiveness of the silicon thin film solar cells. Thus, additional ARL is required at other interfaces such as the glass/TCO interface. To our knowledge this has been scarcely studied. The suppression of reflection at the glass/TCO interface is crucial for effective light management in silicon thin film p–i–n solar cells.

The AR film inserted at the glass/TCO interface should have a refractive index between 1.5 and 1.9. As such, candidate materials are Al₂O₃, CaCO₃, MgO, PbF₂ etc. For a suitable ARL at the glass/TCO interface, high optical transmittance in the UV–vis–NIR wavelength regions is required. In addition, magnetron sputtering is the preferred deposition method for processing compatibility, as the TCO (i.e. Al-doped ZnO) layer is typically deposited by magnetron sputtering in silicon thin film solar cells. Given these considerations, Al₂O₃ or MgO are thought to be the strongest candidates. In this letter, we investigate a magnetron sputtered Al₂O₃ ARL with the purpose of decreasing the reflection at the glass/TCO interface in µc-Si:H p–i–n thin film solar cells.
2. Experiment

Before the fabrication of ARL and μc-Si:H p–i–n thin film solar cells, an optical simulation (ASA, Advanced Semiconductor Analysis) was performed to tentatively investigate the kind of Al2O3 thin film ARL most suitable for this role. Various thicknesses of Al2O3 thin films were considered for use at the glass/TCO interface. After the simulation, sample preparations were carried out to demonstrate experimentally the effects of the inserted ARL. Al2O3 thin films were prepared on corning glass substrates by RF magnetron sputtering. An Al2O3 ceramic target was used and pure Ar sputtering was carried out to deposit the Al2O3 thin films. After the deposition of the Al2O3, Al-doped ZnO (AZO) with a thickness of 1.1 μm was continuously deposited onto the Al2O3 layer by DC magnetron sputtering without a vacuum break. A ceramic AZO (2 wt% Al2O3) target was used to prepare the AZO thin films. The substrate temperature was fixed at 250 °C during the Al2O3 and AZO deposition. For efficient light trapping, the surface texturing of the Al2O3/AZO bi-layer was performed by wet-chemical etching with diluted HCl (0.5%). After, a 30 nm TiO2:Nb (2 wt% Nb2O5) ARL was deposited on the textured AZO at the AZO/Si interface. In order to enhance the Nb-doping effect, the film was annealed in a vacuum break. A ceramic AZO (20–80 nm) showed lower average reflectance than the cell without the Al2O3 layer. In terms of the finding the optimum Al2O3 thickness, the average reflectance continuously decreased with the increase in Al2O3 thickness from 0 to 40 nm, at Al2O3 thicknesses over 40 nm the average reflectance began to increase from its lowest point. These results imply that the Al2O3 thin films can act as an effective ARL in μc-Si:H solar cells and the film with a thickness of ~40 nm exhibits the best AR properties. Based on these simulation results, experiments for μc-Si:H solar cells with an Al2O3 layer at the glass/AZO interface were processed to test the practical effectiveness of the ARL.

3. Results and discussion

In order to find whether the Al2O3 thin film is suitable as an ARL, an optical simulation (ASA) was performed. Optical systems with flat interfaces (GENPRO1 mode) were considered in our reflectance simulations. The GENPRO1 is a subroutine that is a part of the ASA optical simulator. It implements calculation of optical properties of the multi-layer system (reflectance, transmittance, and absorbance) with flat interfaces. In this approach, the reflection and transmission at all interfaces and the absorption in all layers of the system are taken into account. In addition, optical constants of the layers are employed in the simulation.

Fig. 2 shows the optical reflectance of the μc-Si:H solar cells with various Al2O3 thicknesses. Firstly, fluctuations in reflectance curves were observed due to interference effects between the flat interfaces. The inset graph shows the average reflectance as a function of Al2O3 thickness. The μc-Si:H solar cells with Al2O3 film (20–80 nm) showed lower average reflectance than the cell without the Al2O3 layer. In terms of the finding the optimum Al2O3 thickness, the average reflectance continuously decreased with the increase in Al2O3 thickness from 0 to 40 nm, at Al2O3 thicknesses over 40 nm the average reflectance began to increase from its lowest point. These results imply that the Al2O3 thin films can act as an effective ARL in μc-Si:H solar cells and the film with a thickness of ~40 nm exhibits the best AR properties. Based on these simulation results, experiments for μc-Si:H solar cells with an Al2O3 layer at the glass/AZO interface were processed to test the practical effectiveness of the ARL.

Fig. 3 shows the optical constants of the deposited Al2O3 and AZO thin films measured by spectroscopic ellipsometry. In the measurement of Al2O3 thin film, a standard Cauchy relationship was used [13]. In addition, the Tauc–Lorentz model has been employed to model the AZO film. Recently, this model has been applied to dielectric function modeling of transparent conductive oxide [14]. The refractive indices of the Al2O3 and AZO films at 550 nm were 1.69 and 1.87, respectively. To minimize reflection loss at the glass/AZO interface, the ARL requires a refractive index of about 1.67, which was calculated by finding the geometric mean of the two surrounding indices (i.e. \( n_g = \sqrt{n_{Al2O3}n_{Glass}} \) where \( n_g = 1.5 \) (glass), \( n_A = 1.87 \) (AZO)). The refractive index of the deposited Al2O3 (1.69) is very close to the optimum value (1.67). The extinction coefficient values were found to be
negligible in all wavelength regions, implying that incident photon loss caused by absorption in the Al₂O₃ ARL can be neglected.

Before solar cell fabrication, the characteristics of the AZO TCO deposited on the Al₂O₃ ARL were investigated. The variation in physical properties of the AZO is important because it can affect the performance characteristics of the solar cells, such as fill factor (FF). Above all, the crystallinity of the preceding layer influences the subsequent crystalline growth of the AZO film [15,16]. In other words, the polycrystalline growth of the AZO film can be affected by the structural phase of the Al₂O₃ preceding layer. The crystalline orientation of the precursor film can either enhance or hinder subsequent AZO crystal growth. XRD measurements show that a diffraction peak was not detected in the Al₂O₃ deposited on glass, implying that the prepared Al₂O₃ film consisted entirely of amorphous phase materials. Thus, the c-axis crystal growth of the AZO was not affected by the Al₂O₃ precursor without any specific crystalline orientation. Hall measurement data indicates that the resistivity of the Al₂O₃/AZO bi-layer film was 3.6 x 10⁻⁴Ω⋅cm, this is the same as that of the AZO film grown on the glass substrate. From the results, it is thought that the insertion of the Al₂O₃ ARL at glass/AZO interface did not deteriorate the c-axis oriented polycrystalline structure and electrical resistivity of the AZO TCO film.

Fig. 4 shows the optical reflectance of the fabricated μc-Si:H p–i–n solar cells, which can evaluate the AR effect of the proposed Al₂O₃. The μc-Si:H solar cells were deposited on textured AZO substrates. The reflectance of the μc-Si:H cell was decreased in all wavelength regions by employing an Al₂O₃ (40 nm) ARL. This implies that the inserted Al₂O₃ film works well as an ARL in μc-Si:H solar cells. When the experimental results were compared with the simulated data, it was observed that the measured reflectances were smaller than the simulated ones (Fig. 2). This is a result of the surface texturing of the AZO TCO in the experimental unit, as shown in Fig. 1. Light scattering at rough interfaces decreases optical reflectance and increases optical path lengths, which can enhance light absorption in the photo-active layer [4]. The EQE of the μc-Si:H solar cells, deposited, with and without the Al₂O₃ ARL, was measured to evaluate whether a decrease in reflection leads to an improvement in light absorption, the results are shown in Fig. 5. The EQE of the reference cell was increased by applying Al₂O₃ ARL at glass/AZO interface. the results are shown in Fig. 5. The EQE of the reference cell was increased by applying Al₂O₃ ARL, as a result the short-circuit current (Jsc) was increased from 22.7 to 23.5 mA/cm². From these results, we can infer that the optical reflectance was decreased and light absorption was increased by the Al₂O₃ ARL at the glass/TCO interface.

Fig. 6 shows the results of fabricated μc-Si:H solar cells without and with Al₂O₃ ARL. The EQE was increased by AR effect of Al₂O₃ ARL, resulting in the increase of Jsc from 22.7 to 23.5 mA/cm².

![Fig. 3. The refractive index and extinction coefficient of deposited AZO and Al₂O₃ thin films measured by spectroscopic ellipsometry.](image-url)

![Fig. 4. Reflectance of the fabricated μc-Si:H solar cells without and with Al₂O₃ ARL.](image-url)

![Fig. 5. EQE of the fabricated μc-Si:H solar cells without and with Al₂O₃ ARL.](image-url)
The average values and error bars were employed to exhibit the results. The $V_{oc}$ and FF values were similar levels between the cells with and without Al2O3 ARL. The efficiency was improved by the dominant increase of $J_{sc}$.

Fig. 6. The results of fabricated μc-Si:H solar cells with and without Al2O3 ARL. The average values and error bars were employed to exhibit the results. The $V_{oc}$ and FF values were similar levels between the cells with and without Al2O3 ARL. The efficiency was improved by the dominant increase of $J_{sc}$.

4. Conclusions

In conclusion, the Al2O3 ARL was proposed in order to decrease reflection loss at the glass/TCO interface in silicon thin film solar cells with a p–i–n configuration (superstrate type). The magnetron sputtered Al2O3 thin films have a refractive index of 1.67 which is close to the estimated optimum of 1.69 for minimizing the reflection at the glass ($n = 1.5$)/AZO ($n = 1.89$) interface. The optical simulation results employing the optical constants measured for the Al2O3 indicated that the reflectance of the μc-Si:H solar cell is minimized with a 40 nm Al2O3 ARL. Experimental results showed that the reflectance of the fabricated μc-Si:H solar cells was decreased and the EQE was improved by the insertion of the 40 nm Al2O3 ARL. In addition, the $J_{sc}$ was increased from 22.7 to 23.5 mA/cm², and it showed the effect of increasing the device efficiency about 0.3%. Our experimental results suggest that Al2O3 thin films inserted at the glass/TCO can be an efficient method for improving the efficiency of silicon p–i–n solar cells.

Acknowledgments

This work was supported by the Global Leading Technology Program (no. 2011T10010039) of the Office of Strategic R&D Planning (OSP) funded by the Ministry of Knowledge Economy, Republic of Korea.

References