A Novel Coaxial-Structured Amorphous-Silicon p-i-n Solar Cell With Al-Doped ZnO Nanowires

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***Abstract*—A novel coaxial-structured amorphous-silicon (a-Si) p-i-n solar cell with 1-μm-long low-temperature hydrothermally synthesized Al-doped-ZnO (AZO) nanowires was demonstrated for the first time. The conversion efficiency η increased from 3.92% to 4.27% when the intrinsic a-Si thickness was increased from 25 to 150 nm and then decreased to 3.66% when the intrinsic layer thickness was further increased to 250 nm. It was attributed to an excessively thick intrinsic a-Si layer that would decrease the internal electrical field and interfere with charge separation. With the optimum intrinsic a-Si thickness of 150 nm, the conversion efficiency increased from 4.27% to 4.73% when the AZO wire length was increased from 1 to 2 μm. Moreover, the proposed coaxial-structured solar cell exhibited a nearly 46% efficiency enhancement over a conventional a-Si thin-film solar cell.**

***Index Terms*—Al-doped-ZnO (AZO) nanowires, amorphous silicon (a-Si), coaxial structure, solar cell.**

I. Introduction

SOLAR CELLS have been extensively studied due to their potential as clean and reusable energy resources. There are various types of solar cells, including wafer-based [1], [2], thin-film-based [3], [4], dye-sensitized [5], and hybrid organic–inorganic cells [6]. Amorphous-silicon (a-Si) thin-film solar cells have attracted a lot of attention due to their simple fabrication and low cost. However, they still suffer a relatively low-conversion-efficiency value of 9%–10% [7], [8], as compared with crystalline-silicon or tandem cells. As the absorption layer, they also seriously degrade light collection and thus require a thick intrinsic a-Si layer, which effectively absorbs sunlight and generates more carriers [9]. However, an excessively thick intrinsic a-Si layer may greatly decrease the internal electric field and increase the recombination rate of the junction states.

Nanotechnology has been applied to conventional a-Si thin-film solar cells to improve conversion efficiency, with most efforts focusing on antireflection layers [10], [11].

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ZnO nanowires have attracted a lot of attention due to their unique electrical properties and their potential in optoelectronic applications [12], [13]. Many researchers have doped ZnO nanowires with group III elements such as Al, In, and Ga [14], [15] to enhance their conduction properties [16], [17]. Al-doped ZnO (AZO) nanowires with excellent conduction properties and high crystal quality have been reported [18].

Combining the benefits of high conductivity, high transparency, and high specific surface area, we propose a novel coaxial-structured a-Si p-i-n solar cell with AZO nanowires.

II. Device Fabrication

A 200-nm-thick AZO film was deposited on a glass substrate via magnetron sputtering as the seed layer for AZO-nanowire growth. The precursor solution was prepared by mixing 0.025-M zinc nitrate hexahydrate $(Zn(NO_3)_2 \cdot 6H_2O)$ and 0.025-M hexamethylenetetramine in deionized water. Aluminum nitrate nonahydrate $(Al(NO_3)_3 \cdot 9H_2O)$ was then added to the precursor solution to enhance the Zno-nanowire conductivity. The atomic ratio of Al to (Al+Zn) in the mixing solution was controlled at 3 at%. After the solution was stirred for 15 min, AZO-nanowire growth was carried out at 85 °C in a quartz beaker placed in a kettle. The growth time was controlled from 0.5 to 5 h. Finally, the glass substrate was removed from the solution, rinsed with deionized water, and then dried. The AZO wire length was 1–2 μm.

After the hydrothermal growth, n-i-p a-Si was sequentially deposited onto the surface of the AZO nanowires using plasma-enhanced chemical vapor deposition (PECVD). The PECVD growth conditions were using SiH_4 (10 sccm) source gas at a growth temperature of 350 °C, the H_2 dilution ratio R $(H_2/SiH_4) = 10$, a deposition pressure of 1000 mtorr, a radio frequency of 13.56 MHz, and a plasma power density of 0.08 W/cm^2. PH_3 (40 sccm) and B_2H_6/CH_4 (40/40 sccm) were utilized for n^- and p^- doping. The thicknesses of the p-type and n-type layers were both 30 nm, and the thickness of the intrinsic a-Si layer varied from 25 to 250 nm.

A 100-nm-thick AZO layer, which served as a transparent conduction layer, was deposited by sputtering at room temperature. Finally, a 1-μm-thick Al grid, which served as the electrode, was deposited using an electron-gun evaporator. A schematic diagram of the coaxial-structured a-Si p-i-n solar cell with AZO nanowires is shown in Fig. 1.

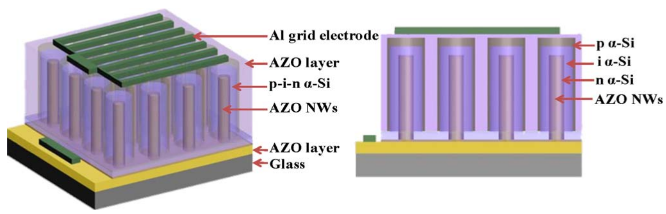

Fig. 1. Schematic diagram of the coaxial-structured a-Si p-i-n solar cell with AZO nanowires.

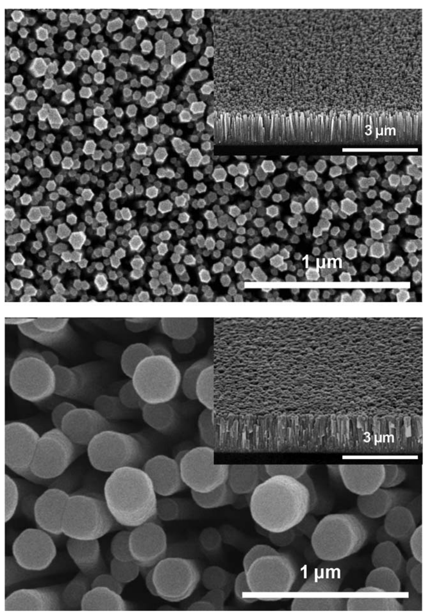

Fig. 2. (Top) Top-view and (inset) cross-sectional FE-SEM images of the as-synthesized AZO nanowires. (Bottom) top-view and (inset) cross-sectional FE-SEM images of the AZO nanowires capped with p-i-n a-Si.

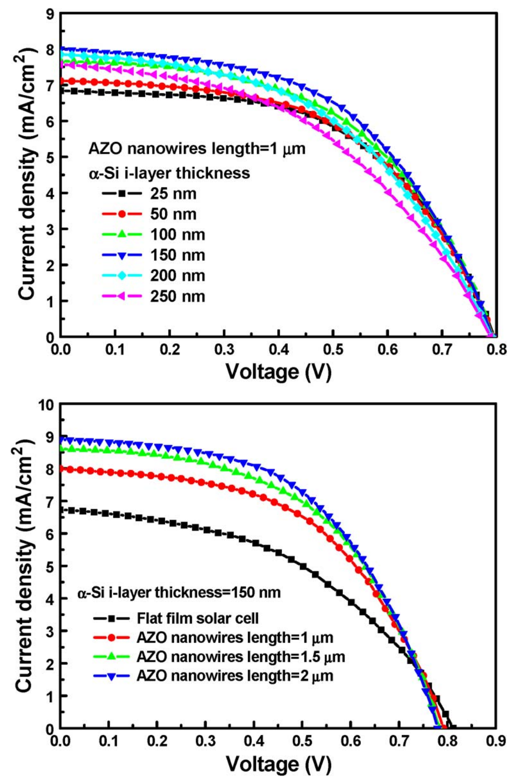

Fig. 3. (Top) I–V characteristics of the coaxial-AZO-nanowired solar cell on the intrinsic layer thickness. (Bottom) I–V characteristics of the coaxial-AZO-nanowired solar cell on wire length.

III. Results and Discussion

The top-view and cross-sectional (inset) field-emission scanning-electron-microscopy (FE-SEM) images of the as-synthesized AZO nanowires are shown in Fig. 2 (top). The dense well-aligned AZO nanowires appear as hexagonal-shaped rods. The average diameter of the AZO nanowires was around 100 nm, and the wire length was around 1 μm. Fig. 2 (bottom) shows the top-view and cross-sectional (inset) FE-SEM images of the AZO nanowires that were capped with p-i-n a-Si. The hexagonal-shaped AZO nanowires became larger and circular after p-i-n a-Si was deposited. It is conjectured that p-i-n a-Si was conformally deposited onto the AZO nanowires.

Fig. 3 shows the current–voltage (I–V) characteristics of the coaxial-AZO-nanowired solar cell and the flat-film solar cell under air-mass-1.5-simulated sunlight illumination. When the AZO wire length was 1 μm, the dependence of the photovoltaic properties on the intrinsic layer thickness is shown in Fig. 3 (top). The result indicates that the short-current density $J_{\rm SC}$ increased from 6.84 to 8 mA/cm^2 and the conversion efficiency increased from 3.92% to 4.27% when the intrinsic a-Si thickness was increased from 25 to 150 nm. However, the short-current density and the conversion efficiency decreased to 7.57 mA/cm^2 and 3.66%, respectively, when the intrinsic a-Si thickness was further increased to 250 nm. A previous study [9] suggested that a thicker intrinsic a-Si layer can absorb more sunlight and generate more carriers. However, an excessively thick intrinsic a-Si layer may cause two adjacent nanowires to have a common i-region; therefore, the radial separation of carriers becomes inactive as carriers in such nanowires will have now to transport vertically rather than laterally, and therefore encounter recombination prior to reaching the contact. In this paper, the optimal i-layer thickness was 150 nm. The dependence of the photovoltaic properties on wire length for the optimal i-layer thickness is shown in Fig. 3 (bottom). The short-current density increased from 7.99 to 8.89 mA/cm^2, the open circuit voltage $V_{\rm OC}$ decreased from 0.79 to 0.77 V, and the conversion efficiency increased from 4.27% to 4.73% when the AZO wire length was increased from 1 to 2 μm. The enhancements in photocurrent and conversion efficiency are attributed to the nanowire structure. Longer wires more effectively absorb sunlight and increase the light-trapping probability. The I–V characteristics of the flat-film solar cell are also shown in Fig. 3 (bottom). The short-current density and the conversion efficiency of the flat-film structure were 6.37 mA/cm^2 and 3.23%, respectively. The proposed coaxial-structured solar cell exhibited nearly 46% efficiency and 32% short-current-density enhancements over a conventional a-Si thin-film solar cell. The coaxial-structured solar cell has a shorter carrier transport path and a radial transport direction, which ensure that carriers reach the contact metal without significant recombination. Moreover, the nanowire structure has an antireflection property and enhances light absorption.

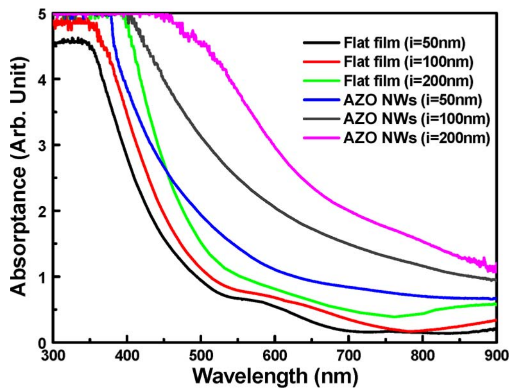

Fig. 4. Optical absorptance of the coaxial-AZO-nanowired solar cell and the flat-film solar cell with the intrinsic a-Si layer varied from 50 to 200 nm.

Fig. 4 shows the optical absorptance of the coaxial-AZO-nanowired sola cell and flat-film solar cell with the intrinsic a-Si absorption layer varied from 50 to 200 nm. The results indicate that more photons were absorbed by the nanowire structure, which can be attributed to its high specific surface area and its excellent light-trapping ability.

IV. Conclusion

A novel coaxial-structured a-Si p-i-n solar cell with low-temperature hydrothermally synthesized AZO nanowires was proposed. The short-current density increased from 6.84 to 8 mA/cm^2 and the conversion efficiency increased from 3.92% to 4.27% when the intrinsic a-Si thickness was increased from 25 to 150 nm. However, the short-current density and the conversion efficiency decreased to 7.57 mA/cm^2 and 3.66%, respectively, when the intrinsic a-Si thickness was further increased to 250 nm. It is ascribed to an excessively thick intrinsic a-Si layer that may cause the radial separation of carriers that become inactive and therefore increase the recombination rate of the junction states. With the optimal intrinsic layer thickness (150 nm), the short-current density increased from 7.99 to 8.89 mA/cm^2, and the conversion efficiency increased from 4.27% to 4.73% when the AZO wire length was increased from 1 to 2 μm. The proposed coaxial-structured solar cell exhibited nearly 46% efficiency and 32% short-current density enhancements over a conventional a-Si thin-film solar cell, which is attributed to the enhanced light-trapping probability and the shortened carrier conduction path.

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