Effects of contact electrode size on the characteristics of polycrystalline-Si p–i–n solar cells

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Abstract: The effects of contact electrode size on the photo-voltaic characteristics of polycrystalline-Si p–i–n solar cells have been studied, with respect to a unit-cell pitch size of 1 μm width. For the non-transparent Al contact electrode with a contact width of 0.05–0.2 μm, the short-circuit current is obviously reduced with increasing contact width, due to a larger area of optical reflection by the electrode. On the other hand, even when using a transparent ITO (indium-tin-oxide) electrode, a larger width of contact electrode may also cause a smaller short-circuit current, due to a larger area of optical absorption by the electrode. However, for this ITO electrode, the contact electrode of 0.05 μm width causes a smaller short-circuit current than that of 0.1 μm width, primarily ascribed to a smaller area for collecting carrier and a larger contact resistance. As a result, while using the ITO contact electrode to enhance the conversion efficiency of the solar cell, a proper width of contact electrode should be employed to optimize the photo-voltaic characteristics.

Key words: polycrystalline-Si solar cell; short-circuit current; transparent contact electrode

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1. Introduction

Since the price of petroleum is getting higher, the clean and almost unlimited solar energy is considered a good substitute energy source. Several technologies in fabricating solar cells have already been developed[1–5]. Polycrystalline or multi-crystalline silicon solar cells have become a strong contender for terrestrial applications[6–10]. In recent years, there has been substantial improvement in the quality of polycrystalline silicon substrates. The effective minority carrier diffusion length has been increased from 80–100 μm to 150–200 μm. However, due to the presence of grain boundaries, subgrain boundaries and impurities, there remains a substantial gap in the efficiency of polycrystalline silicon solar cells when compared with that of single crystalline cells[9, 10].

In addition, since an internal electric field is needed to separate carriers more efficiently, the p–i–n structure has generally been applied in the device structure of solar cells. For the p–i–n structure, the top emitter layer of a heavily doped n^+ or p^+ layer would considerably absorb the incident light. Hence, a thin top emitter layer is generally employed to increase the short-circuit current. However, for a thin emitter layer, the lateral parasitic series resistance would be considerably enhanced as a small width of contact electrode is employed.

In this study, the effects of contact electrode size on the photo-voltaic characteristics of polycrystalline-Si p–i–n solar cells have been studied. Various widths of the contact electrodes have been investigated. Moreover, both the transparent indium-tin-oxide (ITO) electrode and the non-transparent Al electrode have been examined.

2. Device scheme

A typical fabrication process flow of a polycrystalline-Si p–i–n solar cell was carried out. The n^+ poly-Si substrate was heavily arsenic-doped with a concentration of 1×10^{19} cm^{-3}. The poly-Si i-layer was phosphorus-doped with a low concentration of about 1×10^{14} cm^{-3} and with a thickness of about 20 μm. Then, the p^+ layer of about 0.1 μm thickness was formed by heavily boron-doping the poly-Si layer to a concentration of about 1×10^{19} cm^{-3}. The unit-cell pitch size was 1 μm wide, and the longitudinal length of the device was 100 μm. The front contact electrode was formed by the evaporation of 100-nm ITO or Al films onto the wafer, and then the lift-off technique was used for delineation of the contact region. Various front-contact widths of 0.05–2.0 μm were formed to examine the effect on the electrical characteristics of the solar cell, and the contact length was defined as 100 μm.

In addition, the back contact was formed by evaporating Ti/Ag (50-nm/50-nm) on the top of the A1 back-surface-field (BSF) contact region. Figure 1 shows the resultant structure of the polycrystalline p–i–n solar cell. The samples were then annealed in a forming gas ambient for 30 min at 400 ℃. Subsequently, a silicon oxide layer of about 100 nm thickness was deposited on the upper surface for passivation of the solar cell. All of the resultant solar cells were electrically characterized by light measurements. The current–voltage (I–V) measurements were performed with an AM 1.5 g sun simulator under standard conditions (25 ℃, 100 mW/cm^2) to examine the output voltage and the short-circuit current. In addition, the maximum conversion efficiency of the solar cells was calculated from the resultant I–V curve.

3. Results and discussion

The short-circuit current is significantly dependent on the width of the contact electrode. Figure 2 shows the dependence of the short-circuit current on the width of the contact electrode

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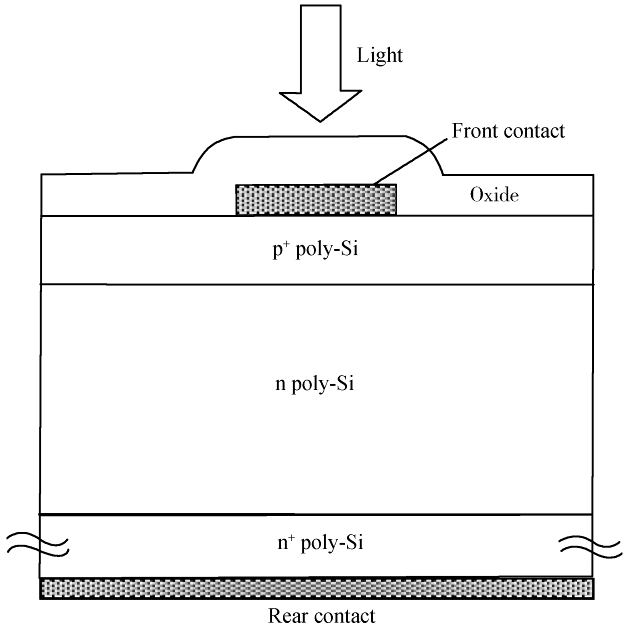

Fig. 1. Resultant structure of the polycrystalline-Si p–i–n solar cell.

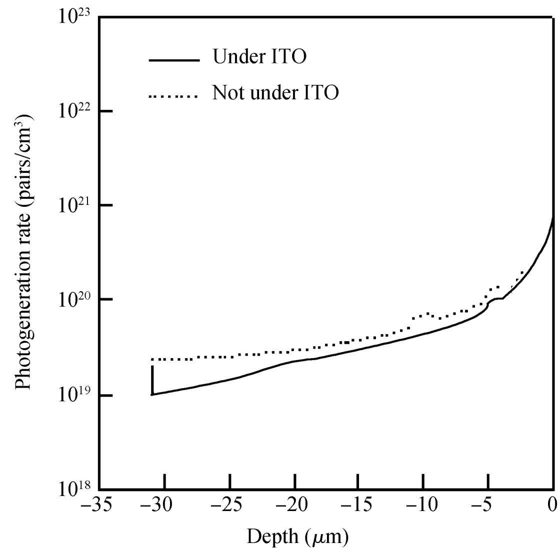

Fig. 3. Carrier photo-generation rate as a function of depth for the devices with and without a transparent contact electrode on the Si layer, respectively.

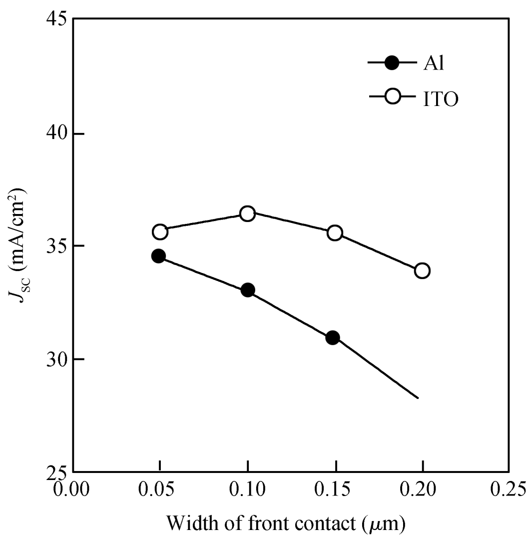

Fig. 2. Dependence of short-circuit current on the width of contact electrode for devices with Al and ITO electrodes, respectively, and with a p^+ layer of 0.1 μm thickness and an i-layer of 20 μm thickness.

for the devices with the Al and the ITO electrodes, respectively. For the Al electrode, the short-circuit current is obviously reduced with increasing width of the contact electrode. The contact resistivity between the Al electrode and the p+ poly-Si is estimated to be about 6 $\mu\Omega\cdot\text{cm}^2$, and the resultant contact resistance is only about 120 Ω, even for a contact width of 0.05 μm. Hence, in terms of the Al electrode, for this short-circuit current of the order of about 10 nA, the resultant $I \times R$ (current×resistance) voltage drop would be only several μV, which implies that the effect of contact resistance on the characteristics of the solar cell is very small. Accordingly, the above result for the short-circuit current would be caused mainly by the fact that much more light is reflected by the Al electrode with a larger area. Thus, the light energy absorbed by the poly-Si layer would be smaller for a larger width of contact electrode.

Since the ITO electrode is much more transparent to light than the Al electrode, the ITO electrode can lead to a much larger short-circuit current than the Al electrode. In addition, as compared to the Al contact electrode, the ITO contact electrode causes much less variation in the short-circuit current with the contact width, due to much better transparency. However, even for the ITO electrode, a large contact width may also slightly degrade the short-circuit current, ascribed to a larger area of optical absorption by the ITO layer. By using MEDICI simulation[11], the carrier photo-generation rate has been calculated. Figure 3 shows the carrier photo-generation rate as a function of depth for the devices with and without a transparent contact electrode on the Si layer, respectively. As a result, even though using the ITO transparent electrode, the carrier generation is slightly reduced. Accordingly, even for the ITO electrode, a small contact width would also facilitate enhancement of the light absorption in the i-layer of the solar cell.

On the other hand, however, a smaller contact width would be worse for collecting the photo-generated carrier, due to a smaller area for the collecting carrier, which may also substantially cause a larger lateral parasitic series resistance. In addition, the contact resistivity between the ITO electrode and the p^+ poly-Si is estimated to be about 30 $\text{m}\Omega\cdot\text{cm}^2$, and the resultant contact resistance is about 600 and 300 kΩ for a contact width of 0.05 and 0.1 μm, correspondingly. For this short-circuit current of the order of about 10 nA, the resultant $I \times R$ voltage drop can be several mV, which may slightly degrade the resultant short-circuit current and the characteristics of the solar cell. Hence, for the ITO electrode, a smaller contact width may cause more serious current crowding and also a larger $I \times R$ voltage drop, thus degrading the short-circuit current. As a result, in spite of the more photo-generated carrier, the ITO contact electrode of 0.05 μm width causes a smaller short-circuit current than that of 0.1 μm width. Hence, for the transparent contact electrode of width smaller than 0.1 μm, both the resultant carrier collection area and the contact resistance may be more dominant in affecting the short-circuit current than the

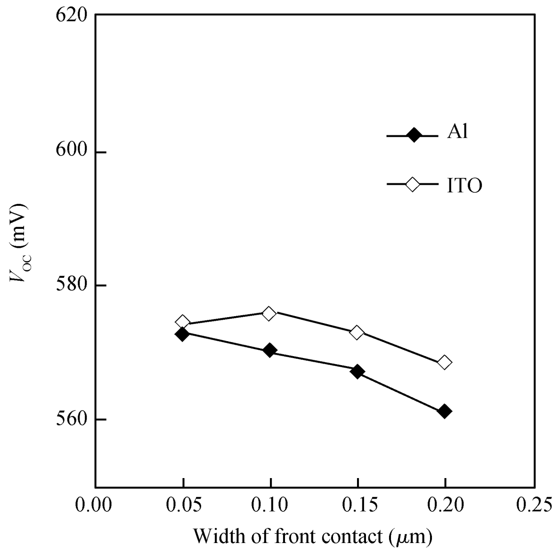

Fig. 4. Dependence of open-circuit voltage on the width of the contact electrode for the devices with Al and ITO electrodes, respectively, and with a p^+ layer of 0.1 μm thickness and an i-layer of 20 μm thickness.

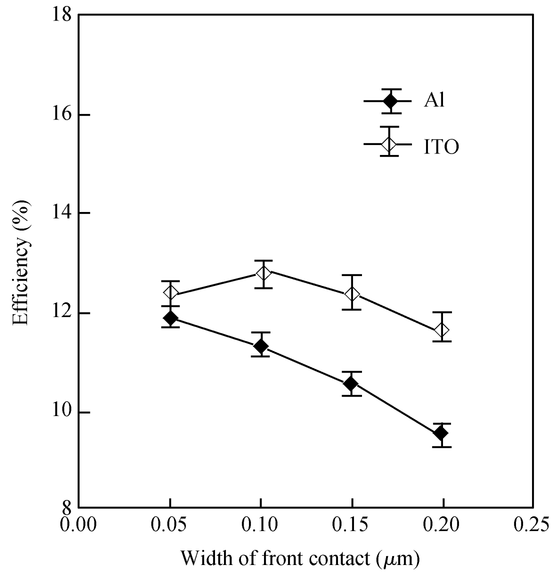

Fig. 5. Dependence of maximum conversion efficiency on the width of the contact electrode for devices with Al and ITO electrodes, respectively, and with a p^+ layer of 0.1 μm thickness and an i-layer of 20 μm thickness.

optical absorption by the electrode.

In addition, Figure 4 shows the dependence of open-circuit voltage on the width of the contact electrode for the devices with the Al and ITO electrodes, respectively. In the p–i–n structure, a forward bias voltage should be provided for inducing dark current. Therefore, a larger forward bias is required to balance a larger short-circuit current, which eventually yields a larger open-circuit voltage. As a result, for the Al electrode, the open-circuit voltage is decreased with increasing width of the contact electrode, which is attributable to the reduced short-circuit current. Similarly, in terms of the ITO electrode, the open-circuit voltage shows a slight decrease with increasing width of the contact electrode, for a width of 0.1–0.2 μm. For a contact width smaller than 0.1 μm, the contact electrode of 0.05 μm width would cause a smaller open-circuit voltage than that of 0.1 μm width, primarily ascribed to a smaller short-circuit current.

In addition, Figure 5 shows the dependence of maximum conversion efficiency on the width of the contact electrode for devices with Al and ITO electrodes, respectively. The deviation in the experimental results is also shown in the illustration. The ITO electrode is found to exhibit larger fluctuation of solar-cell characteristics than the Al electrode, attributable to the worse contact characteristics. Nevertheless, as a result, for the Al contact electrode of 0.05–0.2 μm, the maximum conversion efficiency is increased with reducing contact width. However, for the ITO contact electrode, a proper contact width of about 0.1 μm should be employed to optimize the maximum conversion efficiency, which causes relatively high short-circuit current and open-circuit voltage. Hence, while employing the transparent contact electrode to enhance the performance of the solar cell, the width of the contact electrode should be properly chosen to optimize the photo-voltaic characteristics.

4. Conclusions

The effects of contact electrode width on the photo-voltaic characteristics of polycrystalline-Si p–i–n solar cells have been studied, with respect to a unit-cell pitch size of 1 μm width. For the Al contact electrode of 0.05–0.2 μm width, the photo-voltaic characteristics of the solar cell are improved by reducing the contact electrode width, due to a smaller area of optical reflection by the electrode. Even though using the transparent ITO contact electrode with a width of 0.1–0.2 μm, the short-circuit current is slightly increased with reduced contact width, due to a smaller area of optical absorption by the electrode. However, the contact electrode of 0.05 μm width would cause a smaller short-circuit current than that of 0.1 μm width, ascribed to a smaller area for collecting carrier and a larger contact resistance. For the variation in the open-circuit voltage with the contact width, the results show a trend similar to that of the short-circuit current. Consequently, while employing the ITO contact electrode to enhance the conversion efficiency of the solar cell, a proper width of contact electrode should be employed to optimize the photo-voltaic characteristics.

References

[1] Mukhopadhyay S, Chowdhury A, Ray S. Nanocrystalline silicon: a material for thin film solar cells with better stability. Thin Solid Films, 2008, 516: 6824

[2] Fujiwara K, Pan W, Sawada K, et al. Directional growth method to obtain high quality polycrystalline silicon from its melt. J Cryst Growth, 2006, 292: 282

[3] Malik O, Hidalga W G J, Zuniga I C, et al. Efficient ITO-Si solar cells and power modules fabricated with a low temperature technology. J Non-Crystalline Solids, 2008, 354: 2472

[4] Burgelman M, Nollet P, Degrave. Modelling polycrystalline semiconductor solar cells. Thin Solid Films, 2000, 361: 527

[5] Kaplan R, Kaplan B, Hegedus S S. A comparative study of photoconductivity and carrier transport in a-Si:H p–i–n solar cells with different back contacts. Solid State Electron, 2010, 54: 22

[6] Kunz O, Varlamov S, Aberle A G. Modelling the effects of

distributed series resistance on Suns–V_{oc}, m–V_{oc} and J_{sc}–Suns curves of solar cells. IEEE Photovoltaic Specialists Conference, 2009: 158

[7] Ohdaira K, Takemoto H, Shiba K, et al. Improved performance of thin-film solar cells using surface-morphology-controlled poly-Si films crystallized by flash lamp annealing. IEEE Photovoltaic Specialists Conference, 2009: 26

[8] Lei S, Kunz O, Aberle A. Elimination of hydrogenation-induced contact degradation of evaporated poly-Si thin-film solar cells on glass. IEEE Optoelectronic and Microelectronic Materials and Devices Conference, 2008: 267

[9] Gordon I, Carnel L, Gestel D, et al. Fabrication and characterization of highly efficient thin-film polycrystalline-silicon solar cells based on aluminum-induced crystallization. Thin Solid Films, 2008, 516: 6984

[10] Wang H, Yang H, Yu H, et al. Influence of gettering and passivation on uniformity of the electrical parameters on monolithic multicrystalline silicon solar cell. Solid State Electron, 2003, 47: 1363

[11] Technology Modeling Associates, Inc., MEDICI (two-dimensional device simulation program), Palo Alto, CA, USA, 1996