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Improved carrier extraction of solar cell using transparent current spreading layer

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ABSTRACT

An as-deposited ultra thin metal film was fine-etched to a mesh with average optical transmittance of 70.83%. When this metal mesh was applied to the fabrication of solar cell, it was transparent and conductive to be used as a current-spreading layer. Such a current-spreading layer was good for the carrier extraction of illuminated solar cell. Then the non-uniform two-dimensional current flow on the resistive central emitter region of solar cell can be reduced efficiently by this metal mesh. The metal mesh integrated solar cell can result in improvements of 26.15% for short-circuit current and 30% for the conversion efficiency, respectively.

1. Introduction

In solar cell, reducing the parasitic series resistance is an important way to improve the photovoltaic performance. Generally, the parasitic series resistance results from conductivity of metal electrodes, metal/semiconductor contact, and emitter sheet resistance. Especially, the latest one is the main origin. Specifically, the emitter sheet resistance leads to an operating voltage variation along the surface of emitter [1–3]. This voltage variation is enhanced in the regions between front electrodes (named as "central emitter region"). When the solar cell is illuminated, the resistive central emitter region results in non-uniform two-dimensional current flows gather near the electrodes (i.e. current-crowding). In addition, the discontinuity of atomic structure of semiconductor surface may result in a large number of localized energy states or generation–recombination centers being introduced at the surface region. These energy states, called surface states may greatly enhance the recombination rate at the surface region. The kinetics of surface recombination is similar to those considered for bulk centers. The recombination of carriers will contribute to the series resistance of the solar cell [4–6]. P. Spinelli et al. [7] have presented a Al_2O_3/TiO_2 nano-patterned dielectric coating for crystalline Si solar cells that combines excellent anti-reflection and passivation properties. Although they showed that Al_2O_3 can passivate the Si surface very well, the Al_2O_3 film was deposited by using plasma-assisted atomic layer deposition and annealed at high temperature (400 °C) for 10 min in N_2 environment. This method needs expense equipments and high thermal budget.

Shim et al. used transparent conductive oxide (TCO) material as a current-spreading layer to alleviate the current-crowding issue [8]. Although the TCO materials are transparent [9–14], their conductance cannot satisfy the requirement of high current flow [15–18]. Giurgola et al. [19] proposed a transparent nickel (Ni) film of 2-nm-thick as an alternative in current-spreading layer. However, Ni is expensive and difficult to precisely control the film thickness in Giurgola's work. Thus, we proposed low cost aluminum (Al) as another transparent conducting material to be a current-spreading layer for solar cells. We deposited an Al thin film of 8-nm-thick and etched it slightly to be a mesh. It was found that the completed Al mesh possesses an optical transmittance as high as 70.83% without sacrificing its good electrical properties. When this Al mesh was placed on the central emitter region, it is helpful for extracting more photo-converted carrier so that the current-crowding can be alleviated. The application of Al mesh improved the solar cell very well. With the proposed metal mesh, the short-circuit current and conversion efficiency of solar cell were improved by 26.15% and 30%, respectively.

2. Experimental procedure

The process steps studied in this work were divided into two parts:

(a) Preparation of transparent aluminum mesh
The Al thin film of nanometer thickness (which was denoted as "UTA") was deposited on a silicon substrate by using DC sputtering. The deposition temperature, power density and pressure were 25 °C, 0.27 W/cm^2 and 4 Pa, respectively. The deposition rate was about 0.12 nm/s. Then the UTA film was dipped in a diluted Al etching solution to be fine-etched at 25 °C. The Al

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etching solution was composed of H_3PO_4:HNO_3:CH_3COOH:H_2O = 60.85 (wt.%): 1.95 (wt.%): 12.08 (wt.%): 25.12 (wt.%). The etching rate was about 1000 Å/min. After the fine-etching was completed, a transparent Al mesh can be obtained and denoted as "TAM".

(b) Application of transparent aluminum mesh to solar cell
The tested solar cell was composed of n-type polycrystalline silicon (n-poly-Si)/p-type crystallized Si junction without integrating an anti-reflection layer. In the fabrication, a 100-nm-thick phosphorous doped amorphous silicon (a-Si) film was deposited on a p-type silicon wafer by using plasma enhanced chemical vapor deposition method. The deposition power density, temperature and pressure were 27.4 mW/cm^2, 300 °C and 26.7 Pa, respectively. The gas flow rates for silane (SiH_4) and phosphine (PH_3) were 30 and 20 sccm. After that, the phosphorous doped a-Si film was subjected to a rapid thermal annealing and converted the a-Si into poly-Si to act as the emitter. Subsequently, the Al films were evaporated on both sides of the sample and used lithography to pattern them as the front and rear electrodes. The area of tested solar cell was 1 cm^2. Besides, prior to the photoresist stripping, we fabricated the proposed TAM material as mentioned previously on the central emitter region of the tested solar cell. Finally, the photoresist is removed by the use of ashing method.

The optical transmittance and surface morphology of the transparent samples were measured by UV–vis-IR spectrometer (Holmark HO-SP-S100MA) and atomic force microscopy (AFM; Digital Instrument). Meanwhile, the electrical properties of the processed film were evaluated by Agilent 4156 semiconductor characterization system. The illuminated current-voltage (I–V) characteristics of TAM integrated solar cell was measured under AM1.5 illumination (Pecell Technologies Inc., PEC-L11 model) at 25 °C and the I–V curves were recorded automatically with a Keithley SMU 2410 source meter.

3. Results and discussion

As mentioned previously, the emitter sheet resistance of solar cell results in current-crowding. Meanwhile, the surface states of central emitter region have a profound effect on the emitter sheet resistance. A large amount of photo-converted carriers will be lost on this defective central emitter region. Thus, the addition of current-spreading layer is to provide a conduction path for those photo-converted carriers without passing by the defective central emitter region. In this study, we made a transparent Al mesh as a current-spreading layer to alleviate the current-crowding. The thickness of UTA films was set to 8 nm and 25 nm thick and they were denoted as "UTA_8" and "UTA_25", respectively. Similarly, the respective completed TAMs were denoted as "TAM_8" and "TAM_25", respectively. At the same time, an indium tin oxide (ITO) was also prepared for comparison.

Fig. 1 shows the optical transmittances of ITO, UTAs and TAMs. ITO is the most transparent one with an average optical transmittance as high as 88.7%. On the other hand, those Al samples become more opaque with the film thickness. The average optical transmittances of UTA_25 (20.6%) and TAM_25 (34.5%) are less than 50%. In Fig. 1, TAM_ 8 achieves an average optical transmittance of 70.8%, which is higher than that of UTA_8 (55.6%). Although the optical transmittance of TAM_8 is less than that of the Ni film reported in Giurgola's research, our method can control film thickness, easily. Besides, the features of low cost and good electrical conductance make Al being superior to Ni for transparent conductor application.

Fig. 2 compares the surface morphology of UTA and TAM films. The average surface roughness is 0.34 nm and 1.07 nm for UTA_8 (Fig. 2(a)) and TAM_8 (Fig. 2(b)), respectively. There are many pinholes observed on the TAM_8, which are attributed to the fine-etching. These pinholes can explain why TAM is more transparent than UTA. On the other hand, it was found that there are still some Al films residing on the substrate. Hence, TAM can maintain good electrical paths for carrier conduction.

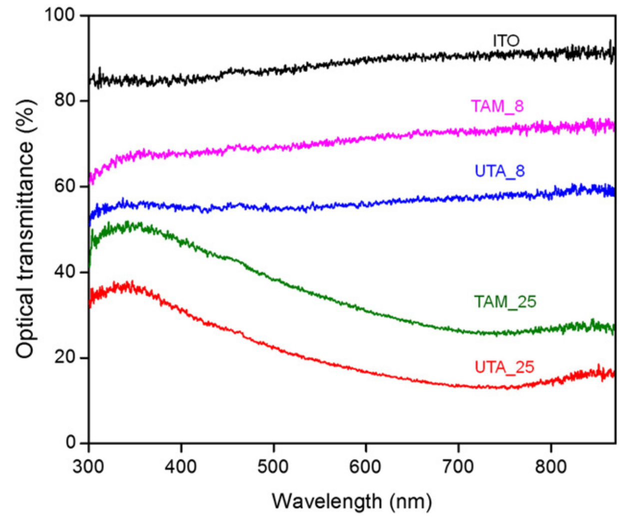

Fig. 1. Comparison of optical transmittances for ITO, UTA and TAM samples.

Fig. 3 shows the I–V characteristics of ITO, UTA and TAM resistors. The tested structure is shown in the inset. The measured resistances of ITO, UTA_8, UTA_25, TAM_8 and TAM_25 are 62, 29.5, 22.5, 48.7 and 25.4 Ω, respectively. It is obvious that the Al samples are conductive more than ITO and thicker Al film can result in lower resistance. In addition, since TAM is produced by etching process, the companied issues such as thinning and damaging make TAM being more resistive than UTA. However, the resistance of TAM is low enough for carrier conduction. If TAM is placed between two electrodes such as the finger electrodes of the solar cell, it is possible that TAM can still provide a

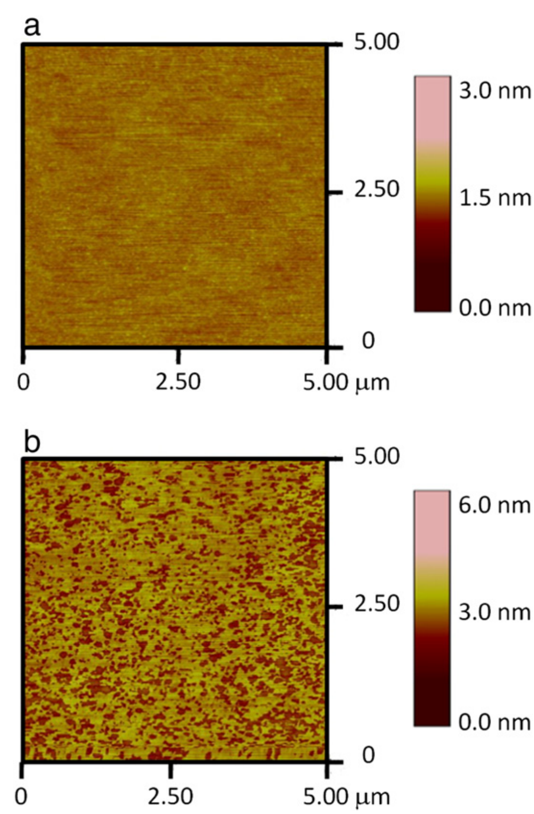

Fig. 2. AFM images, with scale bar inserted, show surface roughness for (a) UTA_8—(RMS 0.34 nm), and (b) TAM_8—(RMS 1.07 nm).