Solar Energy Materials & Solar Cells 144 (2016) 359–363

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Tungsten doped indium oxide film: Ready for bifacial copper metallization of silicon heterojunction solar cell

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ARTICLE INFO

Article history:
Received 6 July 2015
Received in revised form
19 September 2015
Accepted 22 September 2015

Keywords:
IWO film
Copper metallization
Heterojunction
Long term stability

ABSTRACT

Tungsten doped indium oxide (IWO) film was deposited by reactive plasma deposition technology for a-Si:H/c-Si heterojunction (SHJ) solar cell. The average transmittance and absorption of IWO film from 350 to 1200 nm wavelength was 88.33% and 2.16% respectively. The hall mobility is 77.8 cm^2/Vs, with a corresponding carrier concentration of 2.86*E*20 cm^{-3} and resistivity of 2.80*E*−04 Ω cm. Based on high-performance IWO film, the 5 in. SHJ solar cell with efficiency value of 22.03% and power of 3.37 W was obtained by electroplated copper metallization technology. Compared with screen printed SHJ solar cells, the fingers of electroplated cells show finer width, higher aspect ratio and lower series resistance, resulting in increased fill factor and higher efficiency. The long term stability test of copper electroplated cells reveal that IWO film has excellent stability at the solar cell modules' operating temperature and can prevent copper diffusion effectively, which makes copper metallization of high efficiency heterojunction solar cell possible.

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1. Introduction

Silicon heterojunction (SHJ) solar cell has attracted extensive attention due to its excellent passivation, high efficiency, low process temperature and better temperature coefficient, compared to conventional crystalline solar cell [1–3]. Panasonic has presented its bifacial SHJ solar cell with the world's highest cell efficiency of 24.7% [4], and this record has been increased to 25.6% for back contact SHJ solar cell last year [5].

Typically, screen printing low temperature silver paste is the most common technique for SHJ solar cell's metallization. However, this process suffers from low aspect ratio, high contact resistance, high resistivity of low temperature silver paste and excessive shading and high price of silver [6]. Therefore, recent progresses dedicated to metallization of SHJ solar cells are utilizing electroplated copper to replace expensive silver paste as the electrode material, which benefits from reduced optical and electrical losses and can cut the production cost dramatically [7–11]. Hernandez et al. has presented the remarkable results on copper electroplated SHJ solar cell with an efficiency value of 24.2% (aperture area) [12], which are the highest copper electroplated cell for now and show promising application.

Transparent conductive oxide (TCO) film can be seen as the crucial factor to achieve high efficiency and long term stable SHJ solar cell with a copper metallization scheme. Due to the bifacial-ready symmetric structure, the metal electrodes should be deposited on TCO layers directly, while the diffusion of copper into silicon and the reaction with silicon cause electrical performance degradation [13]. In this category, tin-doped indium oxide (ITO) film is usually used with its unique characteristics combining high transparency, low resistivity and excellent adhesion toward metal contact and substrate, but also more absorption at long wavelength band [14–16]. Compared with ITO film, IWO film demonstrates higher mobility, more stable at high temperature and higher transmittance at NIR wavelength region [16–18]. Therefore, IWO film could be a perfect candidate for diffusion barrier, concurrently with contact layer and anti-reflection coating.

In this paper, we deposit IWO film for a-Si:H/c-Si heterojunction solar cell by reactive plasma deposition technology and employ electroplated copper to replace the screen printed silver paste. IWO film displays excellent stability and effective prevention of copper diffusion. The copper electroplated SHJ solar cell shows excellent properties and means great potential to achieve even higher efficiency after proper optimization.

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http://dx.doi.org/10.1016/j.solmat.2015.09.033
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2. Experimental details

2.1. Preparation of SHJ substrates

The n-type c-Si (100) wafers with resistivity of 1–3 Ω cm were used as the substrates. The wet-chemical process was applied to remove saw damage and create a random pyramid surface texture. Both intrinsic and doped a-Si:H layers on the front and rear side were deposited for the emitter and back surface field by plasma enhanced chemical vapor deposition (PECVD), respectively. Then, tungsten doped indium oxide films, with the thickness of 80 nm on the front side and 60 nm on the rear side, were deposited by using a reactive plasma deposition (RPD) system installed with a 1 wt% WO_3-doped In_2O_3 target. The deposition was performed in 20% O_2/Ar mixture at the working pressure of 0.35–0.40 Pa. The substrate holder was maintained at 150 °C during the deposition and the tray speed is 13.8 mm/s. The detailed researches about IWO films could be found in our previous papers [18,19]. Besides, IWO films were deposited on the glass at the same condition to test optical and electrical properties.

2.2. Metallization of SHJ solar cells

Following RPD, the samples were sorted into two groups. Group A was metalized by electroplating Cu/Sn stack layer. Considering electroplating copper on IWO film directly is non-selective, photoresist and photo mask were used for both sides. The unexposed photoresist could then be developed easily to form designed finger pattern, when placed under a UV exposure machine. Thus, selective electroplating was achieved. Finally, photoresist was stripped to form copper electroplated SHJ solar cell. Group B was metalized by screen printing silver grids on both sides and annealed at 200 °C for 30 min.

2.3. Measurement systems

The optical transmittance spectra of IWO film was examined by a Perkin-Elmer Lambda UV/vis/NIR spectrophotometer at a wavelength range from 300 to 2400 nm. Hall measurements for the electrical resistivity, carrier concentration and mobility determination were accomplished at room temperature in an Ecopia HMS-5300 system. Spectroscopic ellipsometer (J. A. Wollam Co., Inc. M-2000) was used to measure the thickness of IWO film to match the thickness proper as an antireflection layer for SHJ solar cell. The geometries of grids were measured by a 3D microscope (Keyence). Finally, SHJ solar cells were characterized by using current–voltage (*I*–*V*) measurements and Suns-Voc system.

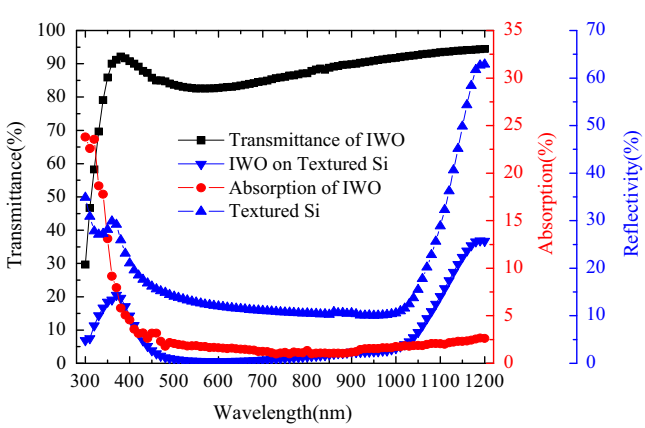

Fig. 1. Optical characteristics of IWO film.

Table 1
Optical and electrical properties of TCO films.

	Band gap (eV)	Mobility (cm^2/Vs)	Carrier concentration (cm^{-3})	Resistivity (Ω cm)	Refractive index @632.8 nm
IWO	3.82	77.80	2.86*E*20	2.80*E*−04	1.99
ITO	3.89	38.24	7.59*E*20	2.14*E*−04	1.97

3. Results and discussion

3.1. Optical and electrical characteristics of IWO film

The optical properties of IWO film's transmission, reflection and absorption are determined by its refraction index, extinction coefficient, band gap, which depend on its chemical composition and solid structure. According to Fig. 1, the average transmittance and absorption of IWO film from 350 to 1200 nm wavelength was 88.33% and 2.16% respectively, which indicate high transparency and low absorption. Considering the band gap of IWO film is 3.82 eV (seen in Table 1), the absorption at short wavelength remarkably increases due to the inter-band optical absorption [20], resulting in the rapid decrease of transmittance from 300 to 350 nm. IWO film was then deposited on textured silicon. Compared to textured silicon, the average reflectivity decreases obviously, from 11.56% to 1.92% at 450 to 1000 nm wavelength band, which means perfect light trapping.

Table 1 compares the optical and electrical properties of IWO film with those of ITO film when both were deposited by RPD system. According to Moss–Burstein effect, the band gap is shifted to higher values at greater carrier concentration. The shift arises because the Fermi energy lies in the conduction band and the filled states block thermal or optical excitation due to the Pauli principle. This explains the band gap of ITO film (3.89 eV) is higher than IWO film (3.82 eV). The resistivity of IWO film is 2.80*E*−04 Ω cm, a little higher than ITO film, while Hall mobility of IWO film is 77.80 cm^2/Vs, exceeding two times higher than ITO film. The resistivity of TCO film is intrinsically limited for two reasons: carrier concentration and mobility. Carrier concentration and mobility cannot be independently increased for practical TCOs with relatively high carrier concentrations. At high carrier concentration, mobility is limited primarily by ionized impurity scattering. Higher doping concentration reduces mobility to a degree that the conductivity cannot increase, and the optical transmission is reduced at the NIR wavelength due to the free carrier absorption. By increasing the concentration of the dopant, the resistivity reduces until lower limit, and cannot decrease further, whereas the optical window becomes narrower. At low carrier concentration, the optical absorption at NIR region is improved, but the resistivity will increase fast. Considering the interrelation of these parameters, mobility is the key factor to make the compromise between optical property and electrical property. IWO film is such a suitable candidate as anti-reflection coating and conductive layer benefited by its higher mobility, which helps to increase conductivity without sacrificing transparency according to the Drude model.

3.2. IWO film-based copper electroplated SHJ solar cell

The total power loss (P_{loss}) of solar cell is limited for two parts: electrical loss and optical loss. Generally, negative correlation is seen between electrical loss and optical loss, and the key way to reduce this correlation is lower finger resistivity with higher aspect ratio. Consequently, the resistivity has a significant influence on the total power loss, especially when the resistivity

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