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Characterization of Transparent Conductive Oxide films and its Influence on Amorphous/Crystalline Silicon Heterojunction Solar Cells

Fanying Meng*[1], Jianhua Shi[1], Leilei Shen[1], Guohe Li[2], Liping Zhang[1], Jinning Liu[1], Yucheng Liu[1], Chenguang Sun[2], Zhiqiang Feng[2] and Zhengxin Liu[1]

[1] Research Center for New Energy Technology, Shanghai Institute of Microsystem and Information Technology (SIMIT), Shanghai 200050, P. R. China
[2] State Key Laboratory of PV Science and Technology, Trina Solar, Changzhou 213031, Jiangsu, China
*Phone: +86-21-6997-6903   E-mail: fymeng@mail.sim.ac.cn

Abstract

Three different dopant indium oxide materials were fabricated at low temperature. The optical and electrical characteristics of TCO films have been analyzed as a function of the hall electron concentration. Furthermore, these TCO films were applied to the amorphous/crystalline silicon heterojunction (SHJ) solar cell as the transparent electrodes. Consequently, the results demonstrated that both higher hall mobility and refractive index of TCO films contribute to higher conversion efficiency and higher product of J_{sc}*FF. Furthermore, it is found that the SHJ solar cell has the high tolerance for TCO resistance when the electron concentration is less than 4.0E-4 ohm cm.

1. Introduction

Amorphous/crystalline silicon heterojunction (SHJ) solar cells are attractive due to their high conversion efficiency, low-temperature process and low LCOE. Thanks to high lifetime of n-type crystalline silicon wafers and excellent surface passivation of hydrogenated amorphous silicon films, the high efficiencies of over 24% have been reported [1,2,3]. However, the main difference of SHJ solar cells from the conventional diffused counterparts is the requirement to apply transparent conductive oxide (TCO) layer on both sides of SHJ solar cell. TCO layers are demanded to collect the carriers and transfer them to the device terminals. The front TCO also serves as an antireflection coating. TCO almost dominates short-circuit current (J_{sc}) and fill factor (*FF*). Therefore, TCO film with excellent optical and electrical properties is vital for SHJ solar cells.

In this work, TCO films doped with three different dopants have been analyzed. Moreover, the influence of TCO films on the SHJ solar cells, especially J_{sc}*FF* and efficiency, has been investigated. Finally, the experimental data have illustrated the effect of hall mobility (μ_H), refractive index (n), extinguish index (k) and electron concentration on the SHJ solar cell performance.

2. Experimental details

W-, Sn-, X-doped In_2O_3 thin films, simplified as TCO1, TCO2, TCO3, were prepared by reactive plasma deposition (RPD) or sputtering at low temperature on glass substrates. High-purity Ar and O_2 gases were introduced into the chamber during the deposition process, the experimental details was depicted in Ref.[4]. All the samples were fabricated at low temperature, after deposition, they have been annealed at temperature of 200℃ in air, which is the same process to the curving step of screen-printed silver grids. After that, the thicknesses, n and k of the films were obtained with spectroscopic ellipsometry of M-2000 system by J.A.Woollam co., Inc., the electrical properties were evaluated by Hall-effect measurement with van der Pauw configuration at room temperature.

3. Results and discussion

3.1 Optical and electrical properties of TCO films

Fig. 1 shows the variation of μ_H and n with the hall electron concentration of TCO films, which demonstrates that μ_H increases with the decrease of electron concentration. Among the discussed TCO films, TCO2 has the low n and μ_H along with high electron concentration, which predicts that J_{sc} would be lower when it is employed to SHJ solar cell than the other two TCO materials. On the other hand, the higher μ_H and n of TCO1 with low electron concentration indicates that J_{sc} would be higher than the other two TCO materials.

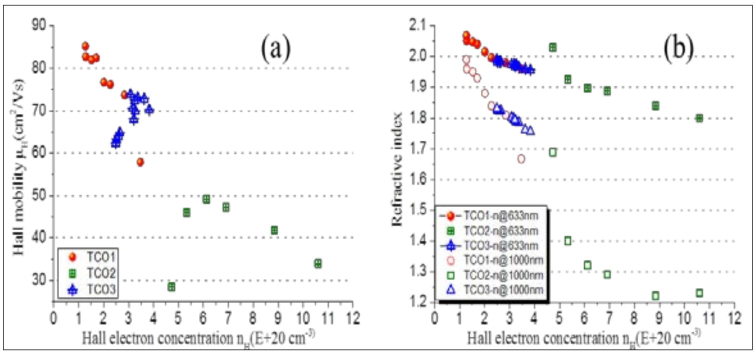

Fig.1 TCO material parameters (a) μ_H vs. electron concentration; (b) n vs. electron concentration.

3.2 Influence of TCO films on SHJ solar cells

According to TCO film characterizations, we applied the TCO films on the SHJ solar cell as the transparent electrodes. SHJ solar cells consist of thin *ip* and *in* a-Si:H stacks deposited by chemical vapor deposition on c-Si wafers. The thickness of the wafer is roughly 100μm. The intrinsic a-Si:H layers can passivate the dangling bonds on the surfaces of Si wafer, the *p/n* a-Si:H layers with n-type wafer can construct the PN junction and back surface field of solar cell. In order to explore the influence of TCO on the

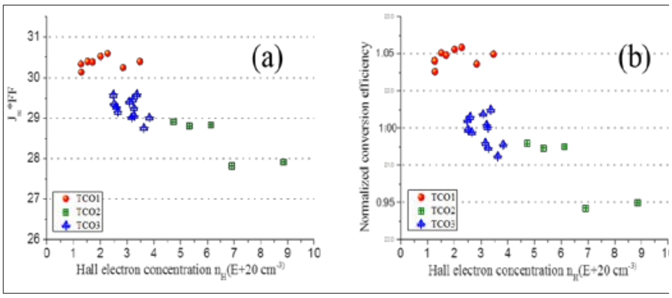

Fig. 2 Dependence of SHJ solar cell parameters on hall electron concentration, (a) J_{sc}*FF vs. electron concentration; (b) normalized efficiency vs. electron concentration.

solar cell performance, the *i/p/n* a-Si:H layers were deposited at the same conditions for all the solar cells, the thickness of the front TCO is approximately 80nm to minimize the sunlight reflection losses. The oxygen partial pressure and the deposition time of TCO films were modulated and the rear TCO is fixed to 80nm. Fig. 2 shows the variation of the product of J_{sc}*FF and conversion efficiency with electron concentrations. Apparently, the behavior of conversion efficiency as hall electron concentration of TCO is quite identical to that of the product of J_{sc}*FF, both of them increase with higher μ_H and n accompanied by lower electron concentration. In addition, in order to understand the influence of TCO on the J_{sc}, the external quantum efficiencies (*EQE*) of SHJ solar cells with 3 TCO films were tested. Fig. 3 illustrates the *EQE* curves. Evidently, the big difference of *EQE* lies in the short-wavelength and visible light regions. The weakest *EQE* from TCO2 is mainly caused by low n and high k (1.80E-2@633nm and1.10E-1@1000nm) as indicated in Fig.1 (b). On the contrary, the strongest *EQE* from TCO3 is attributed to the higher n and extremely low k (1.65E-3@633nm and 7.09E-3@1000nm)in spite of the similar n at 633nm for TCO1 and TCO3, which is probably originated from the better microstructure of TCO3.

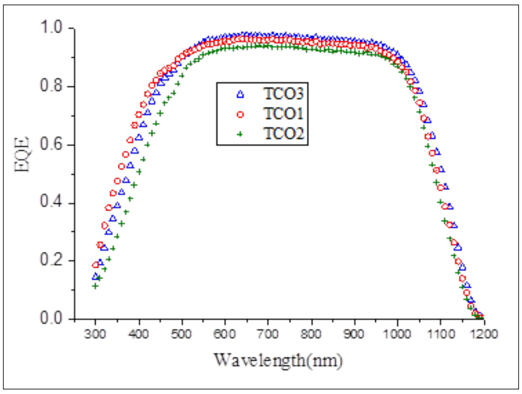

Fig. 3 External quantum efficiencies of SHJ solar cells with various TCO films

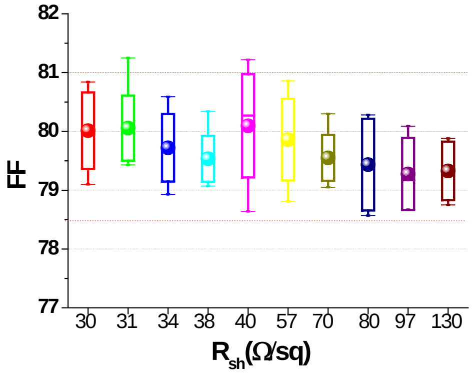

Fig.4 Dependence of *FF* on sheet resistance (R_{sh}) of TCO films

It is well known that the sheet resistance (R_{sh}) of TCO films plays the important role in *FF* of SHJ solar cells. In this work, it is found in Fig. 4 that *FF* is almost stable although R_{sh} was changed greatly from 30Ω/□ to 130Ω/□, *FF* decreases only around 0.5% absolutely from 80% to 79.5% under the condition of electron concentration less than 4.0E+20/cm^3. Obviously, SHJ solar cell has very high tolerance for TCO resistance at the low electron concentration. Based on the optimized fabrication process including TCO films, over 23% of energy conversion efficiency on 5-inch Si wafer (100µm thickness) was obtained in our group.

4. Conclusions

The optical and electrical properties of TCO films doped with 3 different dopants were investigated, it is found from the experimental data that SHJ solar cell has high tolerance for TCO film resistivity when the hall electron concentration is less than 4.0E+20cm^{-3}, furthermore, SHJ solar cell with high performance requires the higher μ_H, higher n and lower k.

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