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ZnS thin film functionalized as back surface field in Si solar cells

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ABSTRACT

A good quality ZnS thin film has been functionalized as back surface field (BSF) in Si solar cells. Compared to Si solar cells without BSF, the solar cells with ZnS BSF presents about 50% increase of the power conversion efficiency (*PCE*). This improvement stems from a downward energy band at the c-Si (n)/ZnS interface, which forms an interfacial field-effect. This field impedes the minority carrier recombination and favors the majority carrier transport, so that open circuit voltage and fill factor of the device are increased. Additional electrode of low work function (e.g. Mg) can further enhance the performance of the solar cell with the ZnS BSF thanks to second downward energy band at ZnS/electrode interface. This work demonstrates that the compound thin film can act as a candidate for a functional layer in Si solar cells.

1. Introduction

Back surface field (BSF) is an important prerequisite for high efficiency Si solar cells, as it contributes to blocking minority carriers and transporting majority carriers for high open circuit voltages (V_{oc}) and fill factors (*FF*). Usually, related-Si BSF has been proved to have a great effect on n-type Si solar cell performance, such as high temperature phosphorus diffused doping in traditional solar cells [1] and gas doping in Si heterojunction solar cells [2,3]. However, the former is done by introducing $POCl_3$ into the furnace about 900 °C, which results in instability and shunting issues. The later forms blocking barriers at hetero-interfaces for the majority carriers due to band offset [4,5]. These problems are not beneficial for device performance improvement. For this, an unrelated-Si BSF has become a better choice for n-type Si solar cells. Not long ago, Mg thin film as BSF is used in hybrid solar cell by Chen et al. [6]. Zinc sulfide (ZnS) is an n-type semiconductor material with direct wide band gap (3.54 eV) [7–9]. Furthermore, ZnS exhibits a nontoxic, abundant raw material and good chemical stability. These advantages made ZnS can be used as a suitable and attractive buffer layer in CIGS solar cell [10,11]. However, Seldom works were reported regarding ZnS application in Si solar cells except for a ZnS/p-Si heterojunction solar cell with a *PCE* of 2.37% [12]. This is because of other overlooked advantages of ZnS, such as a similar lattice constant between ZnS thin film and Si, leading to the good lattice-matching at the ZnS/Si interface. In addition, from the energy bandgap theory, ZnS/Si presents the almost perfect carrier transport property due to their similar electron affinity [13].

In our previous study, we have firstly demonstrated a novel use of ZnS as BSF of n-type Si solar cell through simulation [13]. It is found that ZnS BSF can reach an approximately equal *PCE* with related-Si BSF in n-type Si solar cells due to its proper band alignment. In this work, we experimented ZnS thin film functionalized as BSF of n-type Si solar cells and investigated energy band alignments of both c-Si(n)/ZnS and ZnS/electrode interfaces. An obvious performance improvement was observed in the device with ZnS BSF layer in comparison with that without ZnS.

2. Experimental

The solar cells discussed in this work were fabricated on n-type CZ (100) Si substrates (1–3 Ω cm, 180 μm) after texture, boron-diffusion, PECVD deposition Si_3N_4 and printing front Ag electrode. The above fabrication process was completed on the production line [14]. The back contact layers, such as Ag, ZnS/Ag and ZnS/Mg/Ag (denoted by #1-cell, #2-cell and #3-cell, respectively), were deposited by radio frequency magnetron sputtering from the metal or ceramic target using a power of 120 W, substrate temperature of 200 °C and work pressure of 1 Pa. Under the same condition, about 100 nm ZnS thin film was prepared. Microstructure, crystalline quality and the state of the constituent elements of ZnS thin films on polished Si wafers were characterized using X-ray diffraction (XRD), Photo-luminescence (PL) and X-ray photoelectron spectroscopy (XPS), respectively. The performance of devices (1 × 1 cm^2) were studied by current-voltage (*J-V*) measurement under the standard condition, the external quantum efficiency (EQE) and the impedance spectra (IS).

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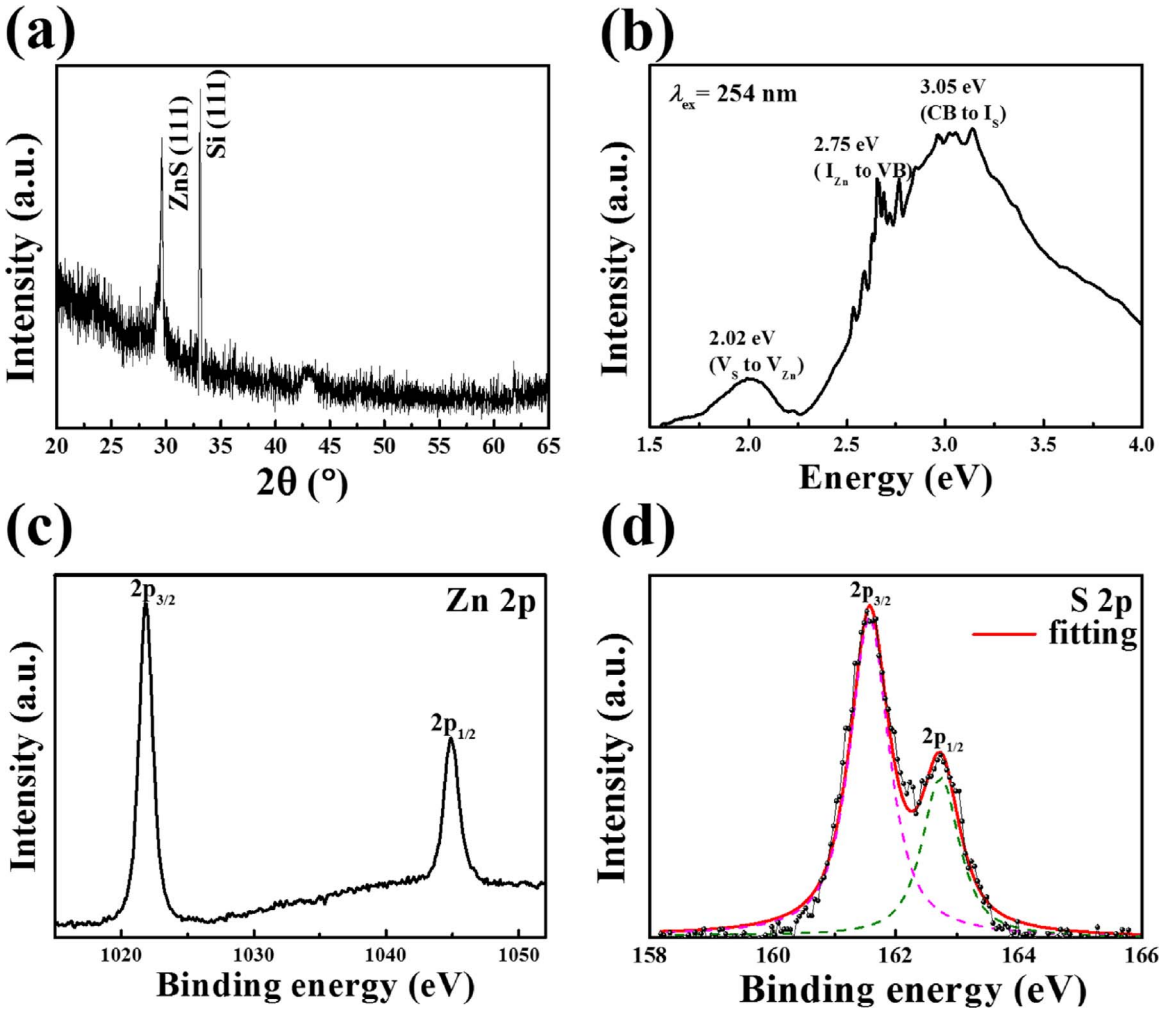

Fig. 1. (a) XRD pattern, (b) PL spectra of ZnS thin film, (b) XPS S 2p spectra (c) XPS Zn 2p of ZnS thin film.

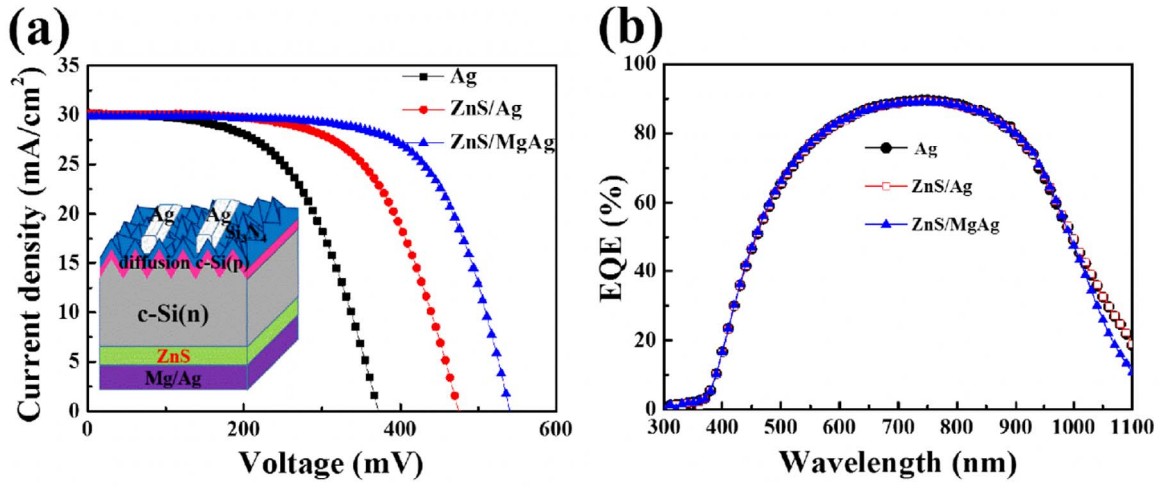

Fig. 2. (a) *J-V* characteristics of the three solar cells and the schematic of #3-cell (insert), (b) EQE spectra of those.

3. Results and discussion

3.1. Structure of ZnS thin film

Fig. 1(a) displays the XRD spectra of ZnS thin film. An only diffraction peak at $2\theta = 29.5^{\circ}$ is observed. This is matched to (111) crystal plane in cubic ZnS according to the reference [9], indicating that ZnS thin film fabricated is well crystallized. Fig. 1(b) shows typical PL spectra of ZnS thin film with 100 nm thick. Two broad peaks at 2.75 eV and 3.05 eV, along with small band at 2.02 eV are observed, which are related to two free-to-band emissions and one donor-acceptor pair transition (related to a sulfur vacancy (V_S) level to a zinc vacancy (V_{Zn}) level) [15–17], respectively. For two free-to-band emissions, the emission at 2.75 eV is associated with a transition from the I_{Zn} level to the