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Optical absorption and photoluminescence of Ag interlayer modulated ZnO film in view of their application in Si solar cells

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Abstract

In this paper, the effect on the optical absorption efficiency and photoluminescence properties of monolayer ZnO and multilayer ZnO/Ag/ZnO films as anti-reflection layers of Si substrates were investigated. By adding Ag thin film to form the sandwich structures, the intensity of Raman scattering was enhanced, and the energy band structure of sandwich ZnO/Ag/ZnO films was optimized by changing the band gap and the Fermi level of ZnO. The absorption efficiency had a remarkable increase caused by interlayer Ag. Noticeably, the absorption efficiency rose several times in 1200–1500 nm region. This Ag interlayer modulated ZnO film can be one of the promising materials used in solar cells.

Keywords: A. Films; C. Optical properties; D. ZnO

1. Introduction

Due to the increasingly serious problems of the energy crisis and environmental pollution, solar energy, which is safe, cheap, inexhaustible and environment-friendly, has been attracting considerable attention. The evolution of crystalline Si (c-Si) solar cells is hindered by the surface reflection loss, especially for the polished flat-Si with high specular reflexivity of 30–40% [1]. The predominant means of enhancing the light absorption are texturing, adding separate structures, providing antireflection coating for the front surface, and designing the back contact [2–6]. However, most of the textured Si surfaces could reduce reflection effectively only in the visible range, so it is necessary to develop solar-blind Si surfaces with the lower reflectance both in the ultraviolet (UV) and near-infrared (NIR) regions [7]. Recently, the dielectric-metal-dielectric (DMD) layer structure, as a low-energy film structure, was confirmed in effectively decreasing the transmitted light in the NIR region, usually by reflection and without affecting visible-light transmission properties [8]. Moreover, Kim *et al.* pointed out that the insertion of a non-absorptive oxide layer between c-Si and Al improved the optical absorption efficiency (OAE) and increased the light absorption in the NIR region according to their simulation results [9].

Zinc oxide (ZnO) is an adequate window material for display in solar cells owing to its high direct band gap with (3.37 eV) to achieve high built-in voltage and high open-circuit voltage [10,11]. In solar cells, the use of an intrinsic and doped ZnO window layer is a promising choice among several transparent conductive oxides to conduct electric currents with low resistive losses [12]. The n-type doping of ZnO with appropriate donor concentration can improve its electronic properties, which have been widely researched [13]. The p-type window layer and its interface with the intrinsic absorber layer play an important role in achieving high performance a-Si:H solar cells [11]. In addition, ZnO can be doped with a wide variety of ions to improve its performance in several fields. Metal-oxides are promising for the broadband transparency with strong absorption capability in the UV region, and

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its electrical conductivity can be improved by doping impurities, such as Al, Ga, In, Sn, Cu, Ag, and Ti [14–16]. For instance, ZnO is favorable for UV absorption [17], and Al-doping increases its electrical conductivity [18]. Moreover, doping metal elements into ZnO can even change carrier characteristics [19]. Silver ions can act as acceptors in ZnO, existing on substitutional Zn sites or in the interstitial form [20,21]. Ren *et al.* have pointed out that Ag acts not only as the electron sinks but also the charge carriers in Ag/ZnO composites [22]. Currently, many researchers are dedicated to investigating the electrical and magnetic properties of ZnO, Al:ZnO/Ag/Al:ZnO film, Ag/n-ZnO/p-Si/Al, Ni/n-ZnO/p-Si/Al heterojunction, and so on [23–30]. However, few studies have been concerned with the optical properties of heterojunction films, especially in the NIR region. Still, the reflectivity of materials is one of the most important parameters in the design process of the optoelectronic devices.

In this work, we studied the optical absorption and photoluminescence of the sandwich ZnO/Ag/ZnO anti-reflection film, which is deposited on Si(100) substrates to better increase absorption efficiency. Moreover, its related morphology, crystal structure, surface modification, energy band structure and contact effect were also investigated.

2. Experimental

The monolayer ZnO film was deposited on single crystal p-Si(100) substrates (thickness: 0.5 mm) at room temperature (RT) and 400 °C by radio frequency (RF) magnetron sputtering technology for 110 min. The deposition parameters were base pressure 5×10^{-5} Pa, RF power 80 W, Ar flow rate 30 sccm and O_2 flow rate 10 sccm, working pressure 0.6 Pa. The target was commercially available ZnO (ZhongNuo Advanced Material (Beijing) Technology Co., Ltd.; ZnO 99.99% purity). The sandwich ZnO/Ag/ZnO films were also prepared on Si(100) substrates (thickness: 0.5 mm) at RT and 400 °C, respectively. First, the ZnO films were deposited with the same deposition parameters for 70 min. Then, the Ag film was deposited by direct current (DC) magnetron sputtering technology at RT. The deposition parameters of Ag were base pressure 9×10^{-5} Pa, DC power 30 W, Ar flow rate 50 sccm, working pressure 0.25 Pa. The targets were commercially available Ag (ZhongNuo Advanced Material (Beijing) Technology Co., Ltd; Ag, 99.99% purity). Next, the ZnO films were deposited with the same deposition parameters for 40 min. The structures of the sandwich ZnO/Ag/ZnO and comparison monolayer ZnO films are shown in Fig. 1. The thickness of each film has been measured by ellipsometer and also given in Fig. 1.

The morphology and crystal structure of the samples were investigated using field-emission microscopes electron microscopy (FE-SEM, JEOL-JSM 7001F, Tokyo, Japan) and X-ray diffraction (XRD; Rigaku Smart Lab). Surface analysis was conducted using atomic force microscopy (AFM; Model SPA300HV, SEIKO, Japan). Raman scattering experiments were performed using a HORIBA Jobin Yvon HR800 Spectrometer with a spectral resolution of $\leq 2\ cm^{-1}$ in the wave number range from 200 to 2000 cm^{-1}. The photoluminescene (PL) measurements were carried out by a Lab Ram HR Evolution micro Raman spectrometer at room temperature. A He–Cd laser operating at 325 nm was used as the excitation. The optical reflectance spectra of the samples were acquired at RT with a Perkin Elmer Lambda 950 UV/Vis/NIR spectrometer, operated in air, at normal incidence, in the 200–1500 nm spectral range.

3. Results and discussion

Fig. 2 shows the XRD patterns of the monolayer ZnO (RT and 400 °C) and sandwich ZnO/Ag/ZnO (RT and 400 °C) anti-reflection films deposited on Si(001) substrate. The peaks located at around 32.9° and 69.1° are attributed to the (002) and (004) planes of Si(001) substrate. And, it is clearly observed that all samples exhibited a dominant peak corresponding to the (002) face of ZnO. For sandwich ZnO/Ag/ZnO films (RT and 400 °C), the peaks corresponding to the (002) plane of ZnO have a slight shift to lower 2θ angle direction in comparison with the monolayer ZnO films (RT and 400 °C). This behavior can be clearly seen in the inset plane (a) of Fig. 1. This is because the ionic radius of Zn^{2+} (0.74 Å) is smaller compared to that of Ag^{+} (1.26 Å) [31]. The intensity peak of the (002) plane of ZnO deposited at 400 °C showed a remarkable increase and another weak peak corresponding to ZnO (004) appeared. This suggests that high deposition

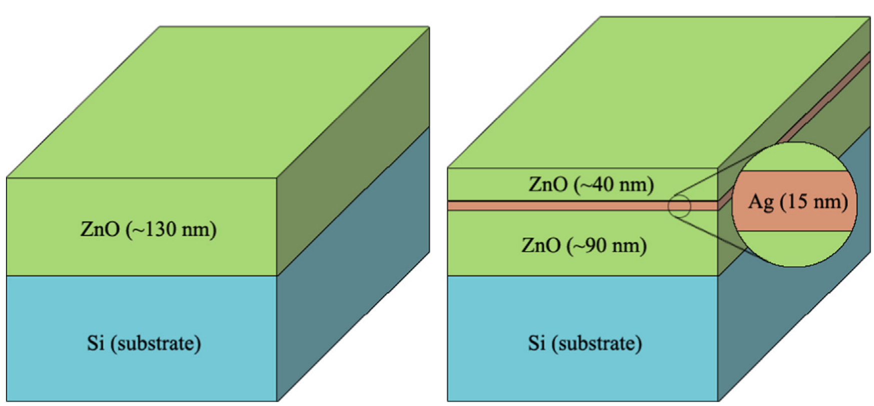

Fig. 1. The structure of the monolayer ZnO and sandwich ZnO/Ag/ZnO anti-reflection films deposited on Si(001) substrate.