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Studies on aluminum-doped ZnO films for transparent electrode and antireflection coating of β-$FeSi_2$ optoelectronic devices

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Abstract

β-$FeSi_2$ can be used for various *optoelectronic* devices owing to its superior material features including high optical absorption coefficient and direct band gap of about 0.8 eV. Due to its high refractive index (>5.6), however, suitable antireflection coating (ARC) is necessary for practical device applications. In order to increase the effective areas of *optoelectronic* devices, transparent electrodes should be also developed. In this work, Al-doped ZnO (AZO) films were fabricated by sputtering on β-$FeSi_2$ thin films and were found suitable for both transparent electrodes and ARC films. Choosing optimum substrate temperature and sputtering rate, high quality AZO films were formed. The conductivity of AZO films was as high as 3×10^3 S/cm and ohmic contact was easily achieved between AZO and β-$FeSi_2$ films, indicating AZO film as an ideal transparent electrode for β-$FeSi_2$. The transmittance of 400-nm-thick AZO films was >80% and >70% in the wavelength ranges 400–1400 and 1400–1600 nm, respectively. By changing the thickness of AZO film, the central wavelength of minimum reflectance was adjusted to 1550 nm where the total reflectance of AZO/β-$FeSi_2$/Si structure was reduced below 2%.

Keywords: β-$FeSi_2$; Zinc oxide; Anti reflection coating; Transparent electrode; Surface; Interface

1. Introduction

Due to its direct band gap value of about 0.8 eV and high optical absorption coefficient ($>10^5$ at 1.0 eV), iron disilicide (β-$FeSi_2$) is expected as to be a strong candidate semiconducting material for light emitting diode, light detector at wavelength around 1550 nm, which matches the least loss of quartz fiber used in the present optical fiber communication field, and for solar cell [1–6]. The ultrahigh optical absorption coefficient (about 50 times higher than c-Si) allows β-$FeSi_2$ solar cells to have very thin thickness (thinner than 1 μm in theory) [2]. The abundant existence of the constituent elements in the earth crust and their non-toxicity are additionally attractive for the application in the photovoltaic field with very low cost.

On the other hand, it has been reported that the refractive index of β-$FeSi_2$ is higher than 5.6 from visible light to near-infrared range [7], implying that up to 40% of the incident light from the air will be reflected on the surface. This is undesirable when β-$FeSi_2$ is used in optical detector and photovoltaic devices. Therefore, it is vital to find out proper materials to reduce the light reflection on the surface.

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Moreover, when the thickness of β-$FeSi_2$ is very thin, the sheet resistance will become high, and thus electrical loss in the film will be increased. It is also necessary to develop transparent conducting electrode (in general: transparent conducting oxide, TCO) material for β-$FeSi_2$, which should have high conductivity and good adhesion with β-$FeSi_2$ film. Not much has been reported on the development of suitable TCO on β-$FeSi_2$ even though a lot of research on the film preparation as well as many trails on the device applications have been presented. Under this circumstance, we attempted to develop proper materials that are available both for the antireflection coating (ARC) and have high electrical conductivity for TCO on β-$FeSi_2$ film. Ordinarily, indium tin oxide (ITO), silicon oxide (SiO_2), aluminum-doped zinc oxide (AZO), etc. are often used on silicon solar cells and other optical devices. Because the refractive index of AZO (n=2.1) is higher than that of ITO (n=~1.8 at visible light range) [8,9], we chose AZO rather than ITO as the candidate of ARC and TCO for β-$FeSi_2$ films. In this work, we fabricated AZO films by radio frequency (RF) sputtering, and studied electrical and optical properties. The AZO films had high conductivity and good ohmic contact with β-$FeSi_2$ films. By changing the thickness of AZO film, the reflectance of AZO on β-$FeSi_2$ was reduced as low as 2%. These results demonstrated the feasibility of using AZO film as ARC and TCO for β-$FeSi_2$ films.

2. Experimental

AZO films were prepared using a magnetron RF sputtering. The base pressure of the sputtering chamber was below 1×10^{-5} Pa. Argon gas (purity: 4 N) was used as sputtering source gas and the pressure was controlled at 1.0 Pa during the sputtering. ZnO containing 2 wt.% Al_2O_3 (50 mm in diameter) was used as sputtering target. For optical and electrical property characterization of AZO films, glass slide (Matsunami, Micro Slide Glass, thickness: 0.8–1.0 mm) and Si wafer were used as substrates. Since it was proved in the previous studies that β-$FeSi_2$ films grow epitaxially with continuous structures on Si(111) substrates [10], we used the same (111)-oriented Si substrates (p-type with resistivity higher than 1000 Ω cm) for AZO deposition. The glass slide substrates were cleaned by organic solution and rinsed with ultrahigh pure water. The Si substrates were cleaned with a standard RCA process and the dangling bonds were terminated with hydrogen atoms. Testing β-$FeSi_2$ films were prepared by a special facing-target sputtering method and the details about the preparation are described elsewhere [10]. β-$FeSi_2$ surface was cleaned with organic solution and etched with 5% HF for about 15 s to remove the surface oxide layer before setting into the sputtering chamber. During film deposition, substrate could be heated by lamp embedded on the backside of substrate. The distance between substrate and target surface was fixed at 60 mm.

The transmittance and reflectance of AZO film on glass were measured with spectrophotometer (Hitachi U-4000) at wavelength range from 200 to 2000 nm. The incident angle of light beam was 5° relative to the surface normal. The crystallinity was examined with X-ray diffractometer (XRD) using a Cu Kα source radiation. The microstructures were observed with scanning electron microscopy (SEM, Hitachi, S-4700) operating at acceleration voltage of 5 kV and emission current of 15 μA. Resistivity and carrier mobility were measured by four-probe and Hall effect using Van der Pauw method. The sizes of specimen were 10×20 mm^2 for optical and 4×4 mm^2 electrical measurements, respectively. Current–voltage (I–V) characteristics were measured by semiconductor characterization system (Keithley 4200) using aluminum wire as lead electrode bonded directly onto AZO surface. The electrodes for all electrical measurements of AZO films were prepared by RF sputtering of aluminum.

For ARC film, we mainly focused on wavelength near 1550 nm, which is utilized in the present quartz fiber communication. AZO single layer, as well as SiO_x and AZO two layers were used for this purpose. In order to calculate the thickness of ARC films and test the correctness of experimental value, we used a software to simulate the surface reflectance. In the simulation, the reflectance values for p- and s-polarized light were dependently obtained. We used averaged value of two polarized light for the comparison with the experimental value.

3. Results and discussion

In order to find the best conditions including RF input power, Ar gas pressure and deposition temperature, etc., for AZO films by RF sputtering, we first used glass and Si substrates with high resistivity, and measured the transmittance and conductivity. It has been reported that the deposition parameters probably induce the lack of oxygen in the deposited film, which affects their electrical and optical properties [11]. Our results showed that the transmittance and conductivity of AZO films only changed with the substrate temperature during the deposition, and they were independent on Ar gas pressure and RF input power. Fig. 1 shows the dependence of transmittance and conductivity of AZO films on glass and Si substrate on the deposition temperature. The transmittance value was extracted from transmittance spectrum measured by spectrophotometer at wavelength of 1550 nm. The transmittance decreases with the increase of the substrate temperature from 160 to 300 °C. On the contrary, the conductivity shows opposite tendency and it increases with the rise of the substrate temperature. When AZO films are deposited on Si (111) substrates with the same conditions as above, the conductivity shows different change tendency from that on glass substrate. It has a maximum value at substrate temperature near 250 °C and the conductivity value is about three times higher than that on glass. We consider