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Fabrication and characterization of n-IZO / p-Si and p-ZnO:(In, N) / n-Si thin film hetero-junctions by dc magnetron sputtering

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Abstract

Using a ceramic target ZnO:In with In doping concentration of 2%, hetero-junctions of n- ZnO:In/p-Si and p-ZnO:(In, N)/n-Si were fabricated by depositing Indium doped n - type ZnO (ZnO:In or IZO) and Indium-nitrogen co-doped p - type ZnO (ZnO:(In, N)) films on wafers of p-Si (100) and n-Si (100) by DC magnetron sputtering, respectively. These films with the best electrical and optical properties were then obtained. The micro-structural, optical and electrical properties of the n-type and p-type semiconductor thinfilms were characterized by X-ray diffraction (XRD), RBS, UV - vis; four-point probe resistance and room-temperature Hall effect measurements, respectively. Typical rectifying behaviors of p-n junction were observed by the current - voltage (I - V) measurement. It shows fairly good rectifying behavior with the fact that the ideality factor and the saturation current of diode are n=11.5, Is=1.5108.10-7 (A) for n-ZnO:In/p-Si hetero-jucntion; n=10.14, Is=3.2689.10-5 (A) for p-ZnO:(In, N)/n-Si, respectively. These results demonstrated the formation of a diode between n-type thin film and p-Si, as well as between p-type thin film and n-Si..

Keywords:n-ZnO:In/p-Si; p-ZnO:(In,N); hetero-junctions; rectifying; Current - voltage.

Ⅰ. Introduction

Zinc oxide (ZnO) has been regarded as promising materials for optoelectronic devices, due to its wide direct band gap of 3.37 eV and large excitedbinding energy of 60 meV [1]. Therefore, ZnO has potential applications in light-emitting diodes (LEDs), laser diodes (LDs) and ultraviolet (UV) detection devices [2-4]. Some especially interesting properties of ZnO are low cost, availability, non toxicity, and high chemical stability, and non harmful environments.

The n- type ZnO film has been deposited on various p-type wafers such as Si [5], GaN [6] and GaN:Al [7]. Among all these attempts, the n-ZnO/p-Si hetero-junction is widely adopted in solar cells and photo detectors [8 - 10] for its low cost and flexibility. Although the research on the optical and electrical properties of the n-ZnO/p-Si hetero-junction have been reported [11 - 13], there are only a few reports showing the relationship between the deposition condition and the electrical properties of the hetero-junction [14].

while the growth of high quality n-type ZnO films

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have been achieved,the fabrication of p-type ZnO thin films for high performance have not been demonstrated. The reproducibility and stability of p-type conductivity is still controversial. The co-doped method was first proposed by Yamamoto and Yoshida, this method can increase the solubility of nitrogen in ZnO with acceptable stability and reproducibility by various techniques, such as ultrasonic spray pyrolysis [1], [15], [16], RF co-sputtering [17].

In this paper, indiumdoped n - type ZnO thin film were deposited on p-type Si (100) wafer to fabricate n- ZnO:In/p-Si hetero-junctions, and Indium-nitrogen co-doped p - type ZnO thin film were deposited on n-type Si (100) wafer to fabricate p- ZnO:(In, N)/n-Si hetero-junctions.

II. Experimental Methods

For the purpose of fabricating hetero-junction of indium doped n-type ZnO on p-type Si (110) wafer, the wafer was used as substrates of the hetero-junction. The starting material was polished p-type silicon with a boron- doping concentration (1.6 x $10^{15}cm^{-3}$) corresponding resistivity of1-10Ω. The wafers were prepared by standard procedure, cleaned and then dipped in 2% HF solution for 1 min to remove native oxide layers. Finally, the wafers were dried in a flow of nitrogen.

By thermal evaporation, Aluminum (Al) electrode was deposited on the back side of Si. The IZO films were deposited by the magnetron sputtering on the silicon substrate from ceramic target of IZO. The concentration of In dopant (purity 99.99%) in ceramic targets is 2wt%. The base pressure inside the chamber was pumped down to less than 10^{-4}torr. The DC power is 80W and the temperature on substrates were kept at 200^{0}C. The sputtering proceeded for 0.5hand Al electrode was annealed on the back side at the same time to form a good ohmic contact. The thickness of IZO films were about 700nm. The junction areas were 1x1cm^{2}. Finally, Silver (Ag) electrode was deposited with a shadow mask on the IZO surface for the top electrode.

ZnO:(In, N) thin fims were also prepared by dc magnetron sputtering from ZnO:In ceramic target. The concentration of dopant Indium in ceramic target was 2 wt% In.

The working pressure, direct current, electrical potential, and the substrate temperature $T_s$were: 3 x 10 $^{-3}$ torr, 0.35 A, 520 V, and 350^{0}C, respectively. The distancebetween the target and substrate, and that of the substrate and edge track of target were kept about 3.5 and 2.5 cm, respectively.

The thickness of thin films was measured by Stylus method (DEKTAK 6M, UAS). Electrical measurements were carried out by a Hall measurement system (HMS-300, ECOPIA) and four-point probe method. The structure of the films was analyzed by an X-ray diffraction (XRD) system (D/max-II with Cu-Kα radiation) and FE-SEM (Hitachi 4700). The optical properties of thin films were determinedby a UV-Vis spectrophotometer (Model PB-10, power 200W, Taiwan). The diode-like-rectifying-characteristic of thin films is determined by current-voltage (I-V) measurements.

III. Results and discussion

3.1. Characterization of thin film n-ZnO:In/p-Si hetero-jucntion.

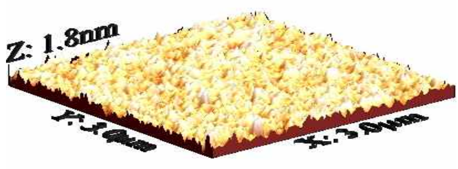

Fig.1. Image AFM of p-type Si (100) wafer after cleaned.

Si substrate has a very smooth surface (the roughness value of root mean square (RMS) is about 1 nm), as shown in Fig.1, which suggests that the substrate is suitable for the synthesis of p-n hetero-junctions.

Fig. 2 shows the XRD spectrumof ZnO:In film on Si wafer, which was deposited by DC magnetron sputtering. The dominant peaks located at 34.31^0 is attributed to the IZO(002) diffraction. The result indicates that the IZO film has a hexagonal wurtzite structure and dominant orientation along the axis perpendicular to the substrate surface.

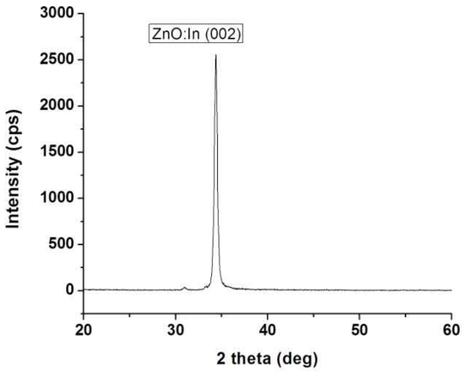

Fig.2.X-ray pattern of the IZO films.

Fig. 3 shows the transmittance spectrum of the ZnO:In film deposited on glass substrate.The transmittance spectrum of the film exhibits an average transmittance over 85% in the visible region.

Electrical properties of the ZnO:In film were measured by four-point probe and Hall effect measurement. The resistivity of the ZnO:In film prepared by dc magnetron sputtering decreases to 1.09 x 10^{-3} Ωm. The carrier concentration and the hall mobility are as high as 6.55 x 10^{20} $cm^{-3}$and 8.78 cm^2/V s, respectively.

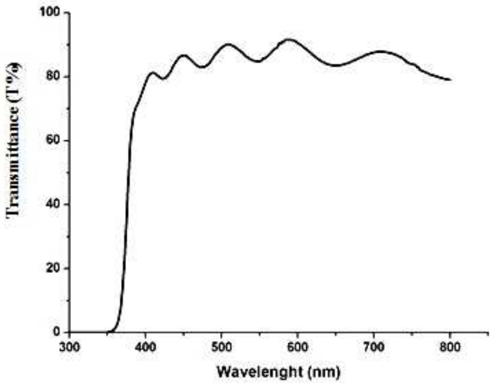

Fig.3.Transmittance spectrum of the IZO film.

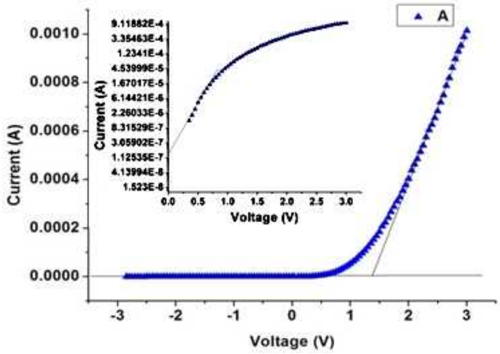

Fig.4. The I-V characteristics of the n-IZO/p-Si hetero-junctions.

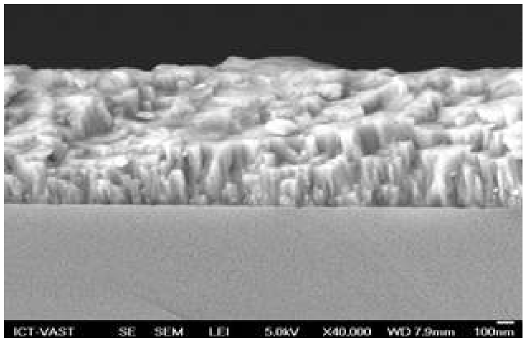

Fig.5. Cross sectional FE-SEM image of n-IZO/p-Si hetero-structure.

Fig.4 shows the room temperature I-V characteristics of n-IZO/p-Si hetero-junction diode. The hetero-junction clearly demonstrates rectifying diode like behavior. The n-IZO/p-Si hetero-junction has the threshold voltage of ~1.4V and a forward current between 0.15 and 1.09 mA.

Fig. 4 shows a semilog plot of I-V characteristics, which indicates that the current at low voltage (V < 2V) varies exponentially with voltage. The characteristics can be described by the stand diode equation [18]:

$$I=I_0(e^{qV/nkT}-1) \quad (1)$$

$$n=\frac{q}{kT}\frac{dV}{d(lnI)} \quad (2)$$

Where q is the electronic charge, V is the voltage at the junction, k is the Boltzmann constant, n is the junction ideality factor, $I_s$is the reverse saturation current, and T is the absolute temperature. The value of the diode ideality factor of n-IZO/p-Si hetero-junctionis determined from the slope of the straight line region of the forward bias log I - V characteristics and using Eq. (2) [19]. At low forward bias (V < 2 V), the typical values of ideality factor and the reverse saturation current are n=11.5, I_s=1.5108.10^{-7} A.

The value of the ideality factor is higher than 2 (value of the ideality factor of diode), which may be due to the effect of series resistance [20]. This result is consistent with FE-SEM analysis. Fig.5 shows a cross-sectional SEM image of the IZO film deposited on p-Si wafer with sputtering power of 80W. The interface between the IZO film and p-Si wafer is flat.

3.2. Characterization of thin film p-ZnO:(In, N)/n-Si hetero-junction.

ZnO:(In, N) thin filmwere deposited on n-Si (100) wafer to fabricate p-ZnO:(In, N)/n-Si hetero-junctions. Fig.6 shows typical XRD pattern of the as-grown ZnO:(In, N) fims on Si wafer. Only one diffraction peak corresponding to the (002) plane is observed indicating preferred c-axis orientation, no other phases corresponding to Zn_3N_2 or In-N peaks are detected obviously.

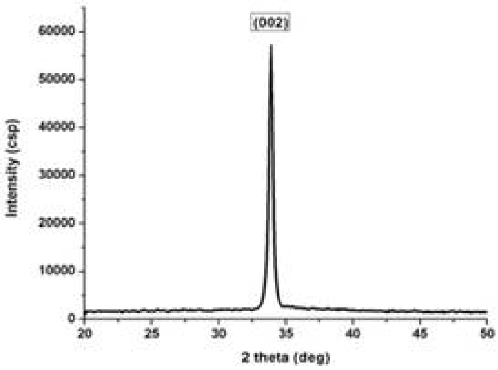

Fig. 6. XRD pattern of In-N co-doped ZnO thin film.

Electrical properties of the ZnO:(In, N) film were measured by four-point probe and Hall effect

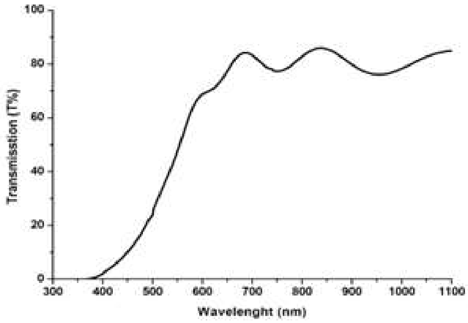

Fig.7. Transmittance spectrum of ZnO:(In, N) film on glass substrate.

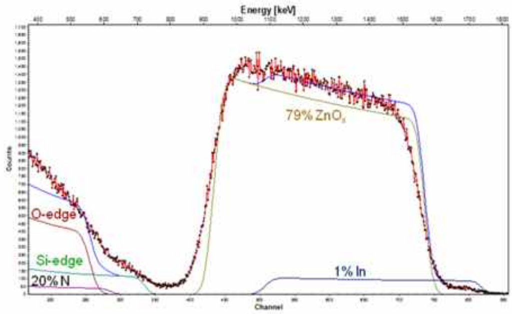

Fig. 8. RBS spectrum of Indium-nitrogen co-dopedZnO film.

measurement. p-type ZnO:(In, N) layer under optimum conditions shows p-type conductivity, with a low resistivity of 0.09 Ωm, mobility of 2.82 cm^2/Vs and hole concentration of $2.26x10^{19}cm^{-3}$, respectively.

For the fabrication of p - n hetero-junctions, the p-type ZnO:(In,N) thin fims were prepared on n-type Si wafer (100) with the optimal conditions such as: direct current of 0.35A; electrical potential of 520 V; working pressure of $3x10^{-3}$ Torr; substrate temperature of 350^0C; the impurities concentrations of In is 2%wt, the gas ratio is 40%N_2:60%Ar. After the thin films are synthesized, the Ag metal to cover on thin film and substrate as electrode.

In order to verify further p-type conduction of the ZnO:(In, N) thin fims, room temperature I - V characteristics of p-ZnO:(In - N)/n-Si hetero-junction diode is investigated and is shown in Fig.9. The hetero-junction clearly demonstrates rectifying diode like behavior, indicating that the p-type conduction is realized in the co-doped thin fim. The p-ZnO:(In - N)/n-Si hetero-junction has the threshold voltage of about0.7V and a forward current between 0.55 and

6.6mA. At low forward bias (V<1 V), the typical values of ideality factor and the reverse saturation current are n=10.14, I_s=3.2689.10^{-5}A, respectively. The value of the ideality factor is higher than 2 (value of the ideality factor of diode), which may be due to the effect of a series resistance.

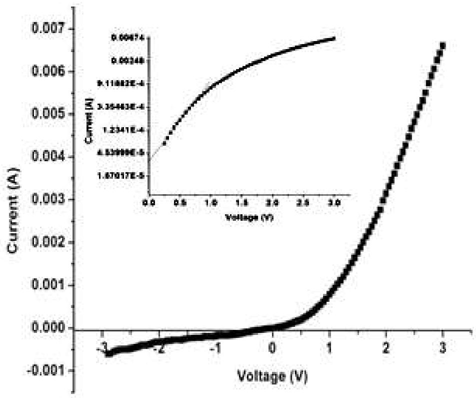

Fig.9. Current - voltage characteristics of the p - ZnO:(In, N)/n-Si hetero-junction.

V. Conclusion

Then-IZO/p-Si and p-ZnO:(In - N) / n-Si hetero-junction have been fabricated by dc magnetron sputtering method. For n-IZO/p-Si hetero-junction, IZO films were fabricated on p-Si wafer for very good electrical properties with resistivity of 1.09x10^{-3} Ωm and the carrier concentration of 6.55x$10^{20}$$cm^{-3}$. The I-V characteristics of n-IZO/p-Si hetero-junction exhibits clearly rectification characteristics. At low forward bias (V < 2 V), the typical values of ideality factorand the reverse saturation current are n=11.5, I_s=1.5108.10^{-7}A, respectively. For p-ZnO:(In - N)/n-Si hetero-junction, the ZnO:(In, N) films were deposited on n-Si wafer, the hetero-junction clearly demonstrates rectifying behavior with n=10.14, I_s=3.2689.10^{-5}A. The I - V characteristics derived from such structure exhibits clearly rectification characteristics, which implies a possibility to fabricate ZnO based on optoelectronic devices such as LEDs and LDs in the future.

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