

A Transparent PN Junction Based on Tin-antimony Oxide Films

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Abstract: Transparent and semiconductive tin-antimony oxide (TAO) films were fabricated by reactive DC magnetron sputtering. According to the results of Hall effect measurement, TAO films are p-type for Sn/Sb atomic ratio in the range of 0.22-0.33, while TAO films with Sn/Sb atomic ratio out of this range are n-type. Optical band-gap measurement results show that the band-gap of all TAO films with various Sn/Sb ratios is almost identical ($\sim 3.91\text{eV}$). Finally, a PN junction based on n-TAO and p-TAO was fabricated using ITO as the electrode for n-TAO and a thin layer of Cu as the electrode for p-TAO. It shows typical rectifying characteristics of a homo-junction diode since both types of TAO films have almost the same band-gap values.

Key words: transparent semiconductive films; antimony-tin oxide; PN junction

Transparent electronics is an emerging electronic technology which employs wide band-gap semiconductors that are transparent in the visible region for the fabrication of electronic and electro-optical devices^[1-15]. Until now, most wide band-gap materials used in transparent electronic devices are transparent conducting oxides films (TCOs). In most cases, transparent electronic devices studied are based on field effect transistors, rather than PN junctions, due to the lack of high quality p-type TCOs. Although progress is making in p-type TCOs by techniques such as co-doping, the electrical and optical characteristics of the p-type TCOs are still not as good as n-type TCOs^[16-21]. On the other hand, although the electrical behaviors of p-type TCOs are not as good as most n-type TCOs, the conductivity of the p-type TCOs is high enough to fabricate transparent PN junctions and other transparent electronic devices.

In a previous paper, we reported a new kind of transparent bipolar conductive oxide films consisting of tin-antimony oxide (TAO)^[19]. It is found that when oxidized at 400°C , the TAO films show p-type conduction with Sn/Sb atomic ratios in the intermediated range (0.22–0.33), while they are n-type with Sn/Sb atomic ratios out of this range. In this paper, a PN junction consisting of p-type and n-type TAO films was fabricated which show clearly typical rectifying characteristics of PN junctions.

1 Experimental details

The PN junction of TAO was prepared as follows. Commercial ITO (indium tin oxide) glass was used as the back electrode and substrate, then a thin layer of about 300nm n-type TAO (Sn/Sb atomic ratio of 0.5) and a thin layer of p-type TAO (Sn/Sb atomic ratio of 0.33) with the same thickness were deposited on the ITO glass successively by reactive DC sputtering. Finally a thin layer of semi-transparent Cu was thermally evaporated as the top electrode, since no heavily doped p^+ -TCO is available yet. The detail of the deposition and characterization of the TAO films have been explained in the reference [19]. The schematic structure of PN junction is shown in Fig. 1.

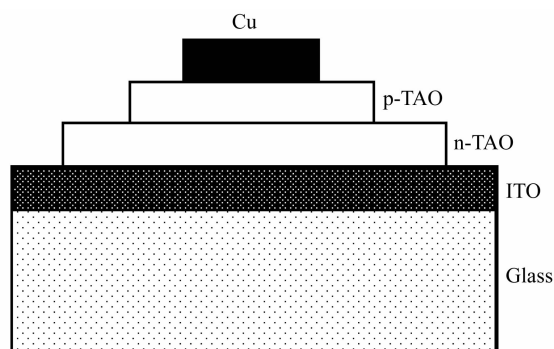


Fig. 1 Schematic structure of the PN junction based on TAO films

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2 Results and discussions

Figure 2 shows the X-ray diffraction patterns of TAO films with various Sn/Sb atomic ratios. It's found that the peak number and the peak positions in all patterns are basically the same, but the relative intensities of the peaks are different. Analysis of the pattern indicates that there exist mainly two phases in the TAO films, *i. e.*, the orthorhombic Sb_2O_4 structure (peaks denoted by diamonds) and the cassiterite SnO_2 structure (peaks denoted by hearts)^[22]. Further qualitative analyses find that for the sample with Sn/Sb atomic ratio less than 0.5, Sb_2O_4 is the dominate phase, while for samples with Sn/Sb atomic ratio greater than 0.5, cassiterite SnO_2 is the dominate phase, as shown in Fig. 3.

The transmittance spectra of TAO films with Sn/Sb atomic ratio of 0.33 is illustrated in Fig. 4. It shows that the films are highly transparent in the visible region. The average transmittance in the visible range ($\lambda = 450 - 850\text{nm}$) is greater than 85%. The optical band-gap of

the TAO film is about 3.91eV, as obtained from the Tauc plot of $(\alpha h\nu)^2 - h\nu$, as shown in Fig. 5. It is noticed that the optical band-gap of TAO films are almost identical for films with various Sn/Sb atomic ratios^[19], which indicates that quasi-homogeneous transparent p-n junctions could be obtained by TAO films.

Further analysis of the transmittance data in Fig. 4 using the method of Jerman, *et al.*^[23], gives the average refractive index value of about 1.9 in the visible range, and the average film thickness of 310nm, according to the envelopes of intensity maxima T_M and minima T_m in Fig. 4.

To measure the $I - V$ curve of the PN junction, ohmic contacts is necessary for both n-type and p-type TAOs. The arrangement of ohmic contact tests are illustrated in Fig. 6. Linear $I - V$ curves were obtained for both n-TAO/ITO and Cu/p-TAO contacts, *i. e.*, $I - V$ curves measured from A-B and C-D is linear, which indicates good ohmic contacts are formed for both n-TAO/ITO and Cu/p-TAO.

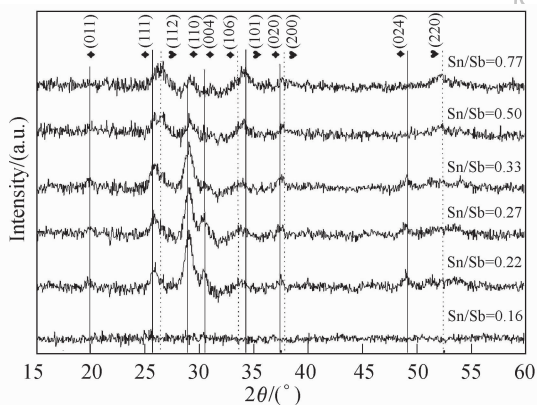


Fig. 2 XRD patterns of the TAO films with various Sn/Sb atomic ratios

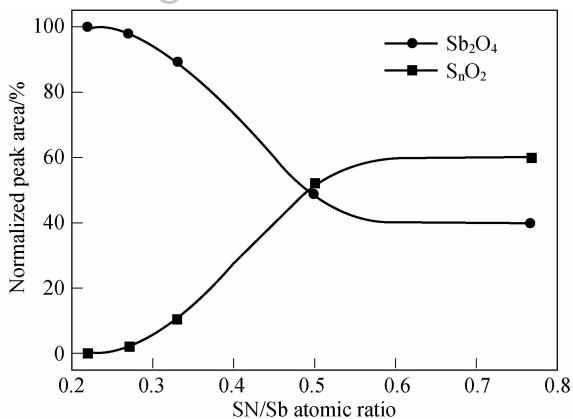


Fig. 3 Normalized XRD peak area of the TAO films with various Sn/Sb atomic ratios

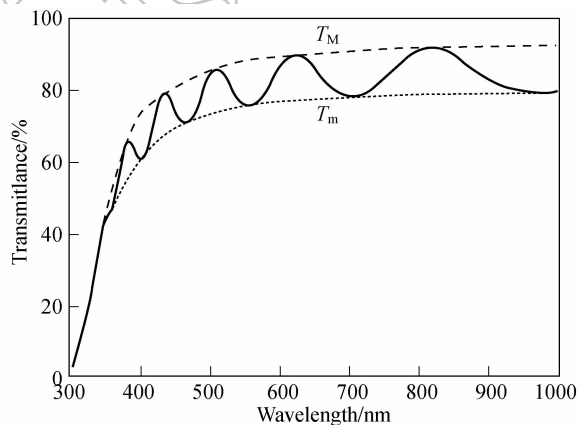


Fig. 4 A typical transmittance spectrum of TAO film with Sn/Sb ratio of 0.33 used to calculate the film thickness

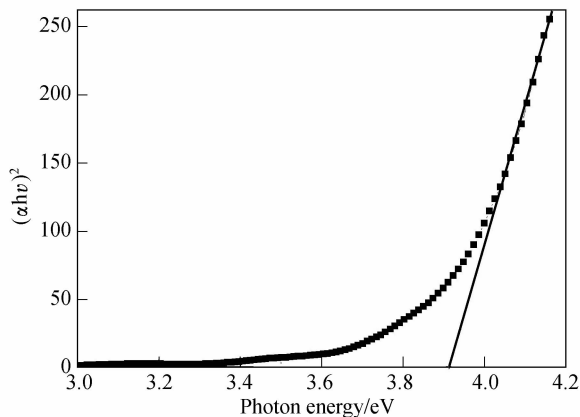


Fig. 5 Optical band gap of the TAO film with Sn/Sb ratio of 0.33 determined by Tauc equation

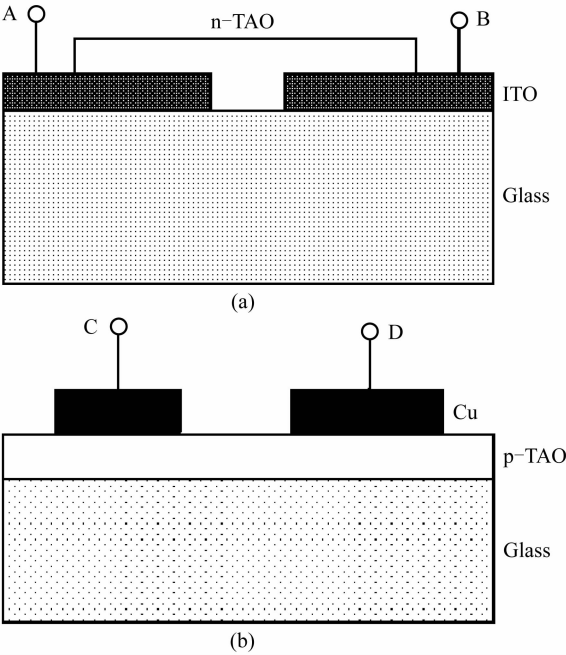


Fig. 6 The arrangement of ohmic contact tests
(a) For n-TAO/ITO; (b) For Cu/p-TAO

Finally, the $I - V$ curve of the PN junction is demonstrated in Fig. 7. As shown in Fig. 7, the $I - V$ curve of the PN junction shows typical rectifying characteristics. The $I - V$ curve of the transparent PN junction look like a traditional homojunction diode, since both n-TAO and p-TAO have almost the same value of the band-gap.

3 Conclusion

In conclusion, a transparent PN junction based on TAO films was demonstrated in this paper. It shows typi-

cal rectifying behavior, and the PN junction is quasi-homogeneous since TAO films with various Sn/Sb ratios have almost identical band-gap values.

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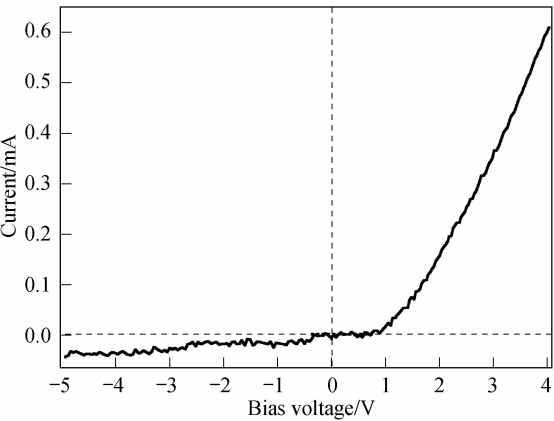


Fig. 7 The $I - V$ curve of a TAO PN junction

一种基于锡锑氧化物的透明 PN 结及整流特性

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摘要: 利用反应磁控溅射法制备了半导体锡锑氧化物薄膜 (TAO). 根据霍尔效应测试结果, 当 Sn/Sb 原子比处于 0.22 ~ 0.33 范围内时, TAO 薄膜是 p 型导电的, 在此范围之外, TAO 薄膜是 n 型导电的. 光学带隙测量结果表明, 不同 Sn/Sb 比的 TAO 薄膜的禁带宽度基本相同 (~3.9 eV). 构造了一个全透明的 PN 结, 其中 n 区为 Sn/Sb 原子比为 0.5 的 TAO 薄膜, p 区为 Sn/Sb 原子比为 0.33 的 TAO 薄膜. n 区 TAO 的电极用铟锡氧化物 (ITO), p 区 TAO 的电极用 Cu 薄膜. 实验结果表明, 由于两种导电类型的 TAO 薄膜具有相同的禁带宽度, 上述透明 PN 结构具有典型的准同质 PN 结的整流特性.

关键词: 透明半导体薄膜; 锡锑氧化物; PN 结

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