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Fabrication of Bottom-Gate and Top-Gate Transparent ZnO Thin Film Transistors*

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Abstract: Transparent zinc oxide thin film transistors (ZnO-TFTs) with bottom-gate and top-gate structures were constructed on 50mm silica glass substrates. The ZnO films were deposited by RF magnetron sputtering and SiO_2 films served as the gate insulator layer. We found that the ZnO-TFTs with bottom-gate structure have better electrical performance than those with top-gate structure. The bottom-gate ZnO-TFTs operate as an n-channel enhancement mode, which have clear pinch off and saturation characteristics. The field effect mobility, threshold voltage, and the current on/off ratio were determined to be $18.4cm^2/(V \cdot s)$, $-0.5V$ and 10^4, respectively. Meanwhile, the top-gate ZnO-TFTs exhibit n-channel depletion mode operation and no saturation characteristics were detected. The electrical difference of the devices may be due to the different character of the interface between the channel and insulator layers. The two transistors types have high transparency in the visible light region.

Key words: zinc oxide; thin film transistor; structure; interface
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1　Introduction

Transparent electronic circuits are promising technologies because of their potential use in next generation optoelectronics devices. A critical element to realize transparent circuits is the transparent transistors[1]. Recently, oxide semiconductors such as zinc oxide (ZnO) have been investigated as active channel layers to construct transparent thin film transistors (TFTs)[2~4]. ZnO is a wide band gap compound semiconductor with hexagonal wurtzite structure. It is attractive because high quality ZnO films with high transparency and moderate Hall mobility can be deposited on various substrates at relatively low temperature[5,6].

Many methods have been used to deposit polycrystalline ZnO films, such as sputtering, pulsed laser deposition, molecular beam epitaxy, etc., and p-type ZnO films[7]. ZnO films would enable the design of complementary logic circuits with a ZnO semiconductor. However, considerable efforts are under way to improve the field effect mobility, decrease the processing temperature, and develop strategies to reduce the carrier density in the channel[8]. There are few reports on the construction of different structures of transparent ZnO-TFTs.

In this work, we report the fabrication of top-gate and bottom-gate ZnO-TFTs. Both of the devices were fabricated by RF magnetron sputtering on 50mm silica glass substrates. We find that different structures produce different electrical properties. The ZnO-TFTs with bottom-gate structure have better electrical performance than those with top-gate structure.

2　Experiments

Figure 1 shows the schematic cross-sectional views of bottom-gate (a) and top-gate (b) structures of transparent ZnO-TFTs. The ITO films were used as gate, source, and drain electrodes and SiO_2 films served as the gate insulator layer. All of the patterned films (ITO, SiO_2, ZnO films) in both the transistors were achieved by standard photolithography and lift-off techniques. The only difference between the two devices is the deposition sequence of the films, i.e., the structures. The ZnO films were deposited by RF magnetron sputtering at room temperature, using a commercially available ceramic ZnO target (99.99%). The sputtering was carried out in a mixed atmosphere of Ar and O_2 with the flow rate ratio of 3∶1. The background pressure was pumped to 6×10^{-4} Pa and the sputtering pressure was maintained at

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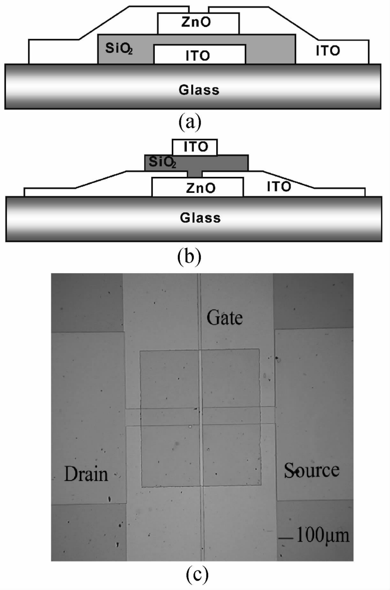

Fig. 1 Schematic cross-sectional illustrations of bottom-gate (a) and top-gate (b) structure ZnO-TFTs Top view optical micrograph (c) of a finished bottom-gate ZnO-TFT taken by an optical microscope

0.8Pa. The distance between the target and the substrate was 70mm and the RF power was 100W. The thickness of ZnO film, measured by surface profilometer, was 80nm. Since they were insulating, the as-deposited ZnO films were submitted to post-thermal annealing at 500℃ in oxygen with a pressure of 10^3Pa for 1h to improve the conductivity. The ITO films with the thickness of 80nm and the SiO_2 films with the thickness of 300nm were deposited by sputtering at room temperature. The channel width (W) and length (L) of the ZnO-TFTs were 100 and 40μm, respectively. Figure 1(c) shows the photograph (top view) of a finished bottom-gate structure ZnO-TFT taken by an optical microscope.

The crystal structure of ZnO films were investigated by X-ray diffractometry (XRD; DX2000) with CuKα radiation ($\lambda = 0.154184$nm) in θ-2θ scan mode. The operation voltage and current were 35kV and 30mA, respectively. The optical transmittance of the ZnO film and ZnO-TFTs was performed with a UV-VIS-NIR double beam spectrophotometer (Varian cary 5000) in the wavelength from 200 to 2000nm. The electrical characteristics of the ZnO-TFTs were measured by a semiconductor parameter analyser (KEITHLEY 4200).

3 Results and discussion

Figure 2 shows the XRD patterns of ZnO films deposited on silica glass substrates. The scan ranged from 20° to 80°. The films have a single hexagonal wurtzite structure with two predominant diffraction peaks corresponding to ZnO(002) and ZnO(004) reflections. The result indicates that the ZnO films were grown with a preferred c-axis orientation perpendicular to the substrate plane. Using the full-width at half-maximum (FWHM) of the ZnO(002) peak from the recorded spectra, the average grain size was on the order of 31nm based on Scherrer formulation[9]. The inset of the Fig. 2 is the optical transmittance of ZnO films. A sharp absorption edge at about 382nm corresponding to the band gap of ZnO was detected and the film has high optical transmittance in the range of 382 to 2000nm. The maximum transmittance is 90%. The electrical properties of the ZnO films were measured by the van der Pauw method at room temperature. The results revealed the electrical resistivity, electron concentration, and Hall mobility of the ZnO films to be 46Ω·cm, $1.5\times10^{15}\text{cm}^{-3}$, and $89\text{cm}^2/(\text{V}\cdot\text{s})$, respectively. All these characteristics demonstrate the ZnO semiconductors can be used in transparent electronic circuits.

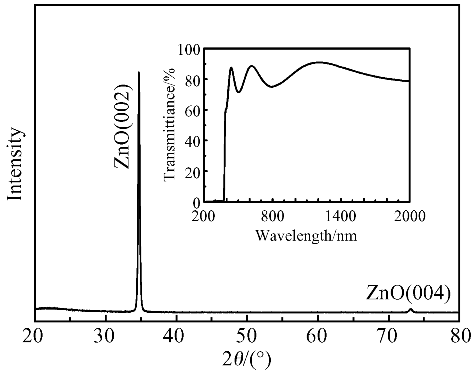

Fig. 2 X-ray diffraction patterns and optical transmittance (the inset) of the ZnO films deposited on silica glass substrate

Figure 3 shows the output characteristics of bottom-gate ZnO-TFTs. The measurements were performed in the dark at room temperature. As the source-to-drain voltage (V_{DS}) at a positive gate bias (V_{GS}) increased, the source-to-drain current (I_{DS}) in-

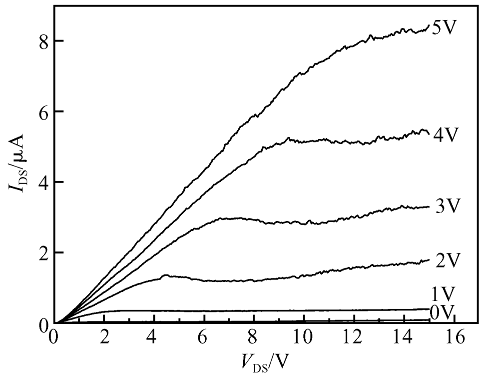

Fig.3 Output characteristics of the bottom-gate structure ZnO-TFTs

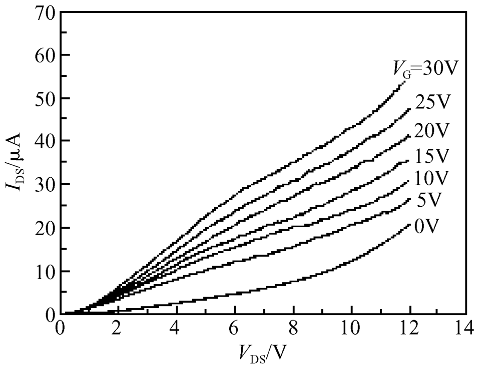

Fig. 4　Output characteristics of the top-gate structure ZnO-TFTs

creased, which implies that the ZnO channel is n-type because a positive V_{GS} is required to induce a conducting channel. The device operated in enhancement mode because of the small drain current at a gate voltage of 0V[10]. The device also exhibited clear current saturation and pinch off characteristics, which is desirable for most circuit applications.

Figure 4 shows the output characteristics of top-gate ZnO-TFTs. Even though the deposition conditions of the ITO, ZnO, and SiO_2 films are the same as those of bottom-gate ZnO-TFTs, the device presents depletion mode performance. There is a large drain current at a gate voltage of 0V and this device has poorer saturated drain current properties. The channel layer is also n-type, but it needs a higher gate bias than bottom-gate ZnO-TFTs to increase drain current. The poor electrical performance of the top-gate ZnO-TFTs may due to the degradation of the ZnO/SiO_2 interface. In our experiment, the sputtering power of SiO_2 films was 200W. The radio frequency induced high energy ions and electrons in the plasma to bombard the deposited ZnO layer, which increased the channel defects. More defects lead to higher carrier concentration and cause the normal-on characteristics of top-gate ZnO-TFTs[11]. Thus, additional work should be done to optimize the deposition of SiO_2 films for high performance top-gate ZnO-TFTs.

The filed effect mobility (μ_{FE}) and the threshold voltage (V_T) can be calculated by the following equation[12] (for the saturation region, $V_{DS} > V_{GS} - V_T$):

$$I_{DS} = \frac{1}{2}\mu_{FE} C_{ox} \frac{W}{L}(V_{GS} - V_T)^2 \quad (1)$$

W and L are width and length of the channel respectively. C_{ox} is the capacitance per unit area of the gate insulator. The transfer curves of the bottom-gate ZnO-TFTs measured at a fixed drain voltage of 10V were shown in Fig. 5. The V_T was extracted by fitting a straight line to the plot of the square root of I_{DS} versus V_{GS} of -0.5V. The device exhibited a current on/off ratio of 10^4 and the off current was approximately 3×10^{-10} A. The μ_{FE} was calculated on the order of 18.4cm²/(V·s) according to Eq. (1), which is an order of magnitude larger than that of amorphous silicon TFTs. The subthreshold swing (S), defined as the gate voltage required to increase the drain current by a factor of 10, is given by Ref. [13]

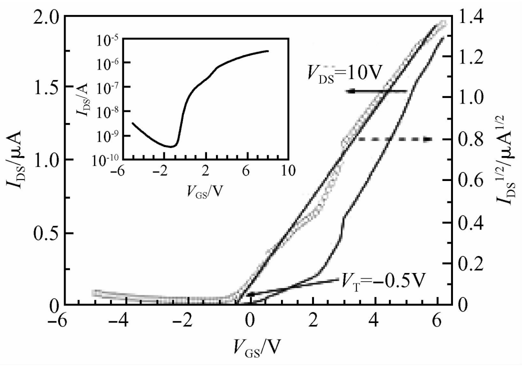

Fig. 5　Transfer characteristics of the bottom-gate ZnO-TFTs (The threshold voltage (V_T) was extracted by fitting the linear portion of the $(I_{DS})^{1/2}$ versus V_{GS} curve)

$$S = \frac{dV_{GS}}{d(\lg I_{DS})} \quad (2)$$

The S was estimated on the order of 1V/decade at the maximum slope in the transfer curve.

Figure 6 presents the optical transmittance of the two types of transparent ZnO-TFTs (including the glass substrate). The devices were highly transparent at higher wavelengths than the absorption edge and exhibited oscillations due to the interference effects. The average transmittance values were on the order of approximately 80%, which indicates that transmission losses due to the ZnO-TFTs in comparison with the substrates are negligible. The inset of Fig. 6 is a photo of a 50mm glass substrate with 44 bottom-gate ZnO-TFTs. Through it, the underlying text is visible, which demonstrates the high transparency of the transistors. All of the results indicate ZnO films can be used as a channel layer of a transparent thin film transistor and will play an important role in future

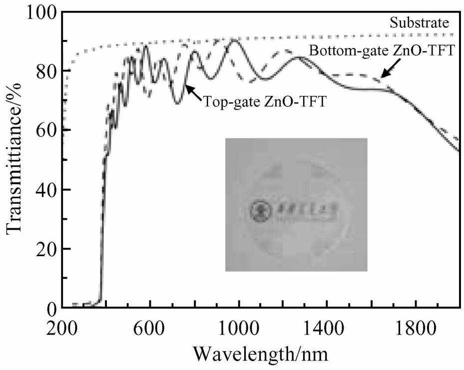

Fig. 6　Optical transmittance of the two ZnO-TFTs types (including the glass substrate)　The inset shows a 50mm silica glass substrate with 44 bottom-gate ZnO-TFTs.

transparent electronic circuits.

4 Conclusion

Transparent ZnO thin film transistors with bottom-gate and top-gate structures were fabricated by RF magnetron sputtering and lift-off techniques. The crystal structure and optical transmittance of ZnO films were investigated by XRD and spectrophotometer. Electrical measurement revealed that the bottom-gate ZnO-TFTs have better behaviors than the top-gate devices. The bottom-gate transistors operate as an n-channel enhancement mode, having clear pinch off and saturation characteristics. The field effect mobility, threshold voltage, and the current on/off ratio were determined to be 18.4cm^2/(V·s), -0.5V, and 10^4, respectively. Both of the devices have high transparency in the visible light spectrum.

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底栅和顶栅结构全透明氧化锌薄膜晶体管的制备*

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摘要： 报道了制备在50mm石英玻璃衬底上的透明氧化锌薄膜晶体管(ZnO-TFT)，采用了底栅和顶栅两种结构进行比较. ZnO沟道层由射频磁控溅射方法制备，SiO_2薄膜作为栅绝缘层. 结果发现底栅结构的ZnO-TFT具有较好的电学性质，该器件工作在n沟道增强模式，具有较好的夹断效应和饱和特性，其场效应迁移率、阈值电压和电流开关比分别为18.4cm^2/(V·s)，-0.5V和10^4. 顶栅结构的ZnO-TFT则工作在n沟道耗尽模式，没有明显的饱和特征. 不同结构ZnO-TFT电学性质的差别可能是由于不同的ZnO/SiO_2界面特性所致. 两种结构的ZnO-TFT在可见光波段都有很高的光学透过率.

关键词： 氧化锌；薄膜晶体管；结构；界面

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