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# Preparation and electrical properties of N-doped ZnSnO thin film transistors

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The preparation and electrical properties of N-doped ZnSnO (ZTO: N) thin film transistor (TFT) with a staggered bottom-gate structure were studied in this paper. ZTO: N thin film, which served as the active layer of the prepared TFT, was deposited on $SiO_2$/p-type Si substrates by radio frequency magnetron sputtering at room temperature. Secondary ion mass spectroscopy (SIMS) analysis results showed all the species (Zn, O, Sn and N) were uniformly distributed in the thin film. X-ray Diffraction (XRD) patterns and scanning electron micrograph (SEM) images indicated that the thin film transformed from amorphous to crystalline states due to annealing. X-ray photoelectron spectra (XPS) proved that the oxygen-related defects in the thin film decreased after annealing. The thin film before and after annealing both showed a good optical transmittance of over 80% in visible light region. The TFT prepared with the thin film exhibited n-channel enhancement mode behavior and showed good electrical properties with a saturation mobility of 41.8 $cm^2V^{-1}s^{-1}$, a threshold voltage of 5.4 V, and an on/off current ratio of $6.5 \times 10^7$.

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## 1. Introduction

Thin film transistor (TFT) is one of the indispensable components in the flat panel display field, where it is generally used as the switching device or the peripheral driver. As known to all, the semiconductor active layer of the TFT plays a dominant role in determining its electrical performance and application. In the past few decades, amorphous silicon (a-Si) or polycrystalline silicon (p-Si) has been widely used as the semiconductor active layer of the TFT. Nevertheless, as the display technology continues to move forward, gradually these Si-based TFTs can't meet the requirement of the times. This is mainly because amorphous silicon TFTs have a relatively low mobility ($<1cm^2V^{-1}s^{-1}$) and polycrystalline silicon TFTs suffer from non-uniformity against large-area preparation. Besides, neither of them is transparent in the visible light region. This makes them unsuitable for transparent applications. Transparency is one of the key issues for future display technology [1–5]. As a result, developing new-type TFTs to get rid of these shortcomings is imperative.

In recent years, considerable attention has been paid to metal oxide semiconductors because metal oxide semiconductors can make the TFTs which use them as active layers obtain superior properties, including large mobility, good optical transparency in the visible region and excellent uniformity over large areas [1,6–11]. In-based metal oxide semiconductors such as InZnO, HfInZnO, InGaZnO, etc., which have been extensively investigated, are typical examples of them. In makes an important contribution to the improvement in the mobility of the TFTs utilizing the In-based metal oxide semiconductors as active layers, which benefits from its special electronic configuration of $(n\text{-}1)d^{10}ns^0$ (n is the principal quantum) [12,13]. However, In belongs to a kind of toxic, rare and expensive metals, which limits its further and extensive application to electronic industry. Therefore, it is common desirable to develop a well-resourced, low-cost and environmentally sound In-free metal oxide semiconductor with similar performance as an In–based metal oxide semiconductor [14,15].

As known to all, not only does Sn have a similar electronic configuration with In, but also it is a kind of in-noxious and

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inexpensive materials. Thus, Sn-based metal oxide semiconductors without In are regarded as competitive alternatives for In-based metal oxide semiconductors. ZnSnO (ZTO) is one example of the Sn-based metal oxide semiconductors without In and the ZTO TFTs with the mobility of 4.54–28 $cm^2V^{-1}s^{-1}$ have been prepared [16–19]. But the ZTO TFTs don't achieve the desirable performance because residual electrons, which are produced by oxygen vacancies ($V_O$), usually exist in ZTO films, giving rise to deteriorated performance of the transistors such as large off currents and/or the depletion mode with large threshold voltages [20]. For resolving these problems, researchers have tried incorporating Mg, Al, Si, Zr, Hf, and Ti, respectively, into ternary ZTO systems to act as $V_O$ suppressors or stabilizers. The elements are able to combine with oxygen to suppress the formation of $V_O$ in the ZTO, but the saturation mobility of the corresponding TFTs are not too high: the saturation mobility of the MZTO TFT [21], AZTO TFT [22], SZTO TFT [23], ZZTO TFT [24], HZTO TFT [25,26] and TZTO TFT [27] are about 0.27, 10.1, 1, 4.02, 1.147 and 4.1 $cm^2V^{-1}s^{-1}$, respectively. N, which is a suitable candidate for substituting O, is abundant in nature. Lim et al. and Liu et al. introduced N into the ZnO and InGaZnO system by $NH_4OH$ solution and reactant gas $N_2$, respectively, and the introduction of N suppressed the formation of $V_O$ and improved electrical properties of the corresponding TFTs [28,29]. This provides a good enlightenment and an important reference for us, and so, with the aid of radio frequency magnetron sputtering, we try introducing N into active layers of TFTs directly by utilizing the N-doped ceramic target which was made through solid phase method [30–34]. However, until now, there have been no reports about ZTO: N TFTs prepared with this method.

In this study, the ZTO: N TFTs with a bottom-gate structure were prepared by radio frequency magnetron sputtering, and the physical and electrical properties of the ZTO: N TFTs were mainly investigated. The prepared ZTO: N TFTs achieved a saturation mobility ($\mu_{SAT}$) of 41.8 $cm^2V^{-1}s^{-1}$, a threshold voltage ($V_{TH}$) of 5.4 V, and an on/off current ratio ($I_{ON}/I_{OFF}$) of $6.5 \times 10^7$.

## 2. Experiments

The bottom-gate N-doped ZTO TFT was prepared in this work. The schematic illustration of the TFT was showed in Fig. 1. The heavily doped p-type Si (111) was used as the substrate and the gate electrode of the TFT. The 300 nm thick $SiO_2$, which was thermally grown on the top of the Si substrate, acted as the gate insulator layer of the TFT. The 37 nm thick ZTO: N thin film, which was deposited on the $SiO_2$ by radio frequency magnetron sputtering at room temperature, served as the active layer of the TFT. The 120 nm thick Al film, which was evaporated on the active layer and the backside of the p-type Si substrate by thermal evaporation, acted as the drain/source and gate electrodes, respectively. During the ZTO: N thin film deposition process, the detailed technical parameters were as follows: a base pressure of $2 \times 10^{-3}$ Pa, a working pressure of $2 \times 10^{-2}$ Pa, a sputtering power of 100W, and a distance of 5.5 cm between the substrates and the N-doped ceramic target. The N-doped ceramic target was made by sintering the mixture consisting of ZnO, SnO, and $Zn_3N_2$ powders by the Zn:Sn:N molar ratio of 7:3:0.01. The used substrates included $SiO_2$/p-type Si substrates and quartz substrates. The quartz substrates were only used for carrying out XRD measurements and optical transmittance measurements of the ZTO: N thin films, and the $SiO_2$/p-type substrates were used for carrying out the other measurements in this paper. It was worth mentioning that to remove possible contaminants in the surface of the ceramic target, pre-sputtering was carried out continuously for 20 min before the thin film deposition process. After the process of the thin film deposition was completed, some of the samples were subjected to thermal annealing at 635 °C for 30 min under a highly pure oxygen environment. In the fabrication process of electrodes, Al source/drain electrodes on the active layer were patterned through a shadow mask with a channel width ($W$) of 50 μm and a channel length ($L$) of 50 μm, and Al was evaporated onto the backside of the p-type Si substrates for the formation of ohmic contact.

The transmittance spectra of the thin films was measured by a Shimadzu UV3101. The structural property of the thin films was determined by X-ray diffraction with Cu Ka radiation (Bruker D8 ADVANCE XRD). The surface morphology of the thin films was studied by using a ZEISS Ultraplus model field emission scanning electron microscopy (FESEM). The chemical composition and bonding states of oxygen in the thin films were examined by X-ray photoelectron spectroscopy (XPS, K-Alpha model, Thermo Fisher Scientific). The distribution of the species in thin film was established by SIMS (TOF.SIMS 5-100). The thickness of the samples was measured by an Ambios Technology XP-2 stylus profilometer. Output and transfer characteristics of the ZTO: N TFT were measured by using a Keithley 4200 SCS/CVU semiconductor characterization system in dark.

## 3. Results and discussion

Fig. 2 shows the SIMS profile of the ZTO: N thin film annealed at

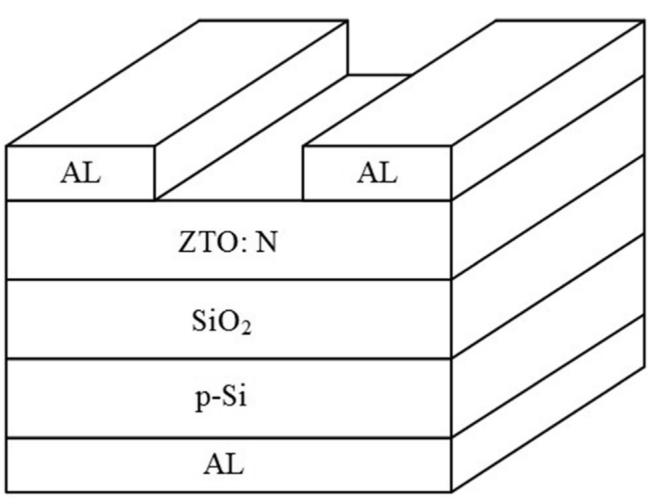


**Fig. 1.** Schematic illustration of the bottom-gate ZTO: N TFT.

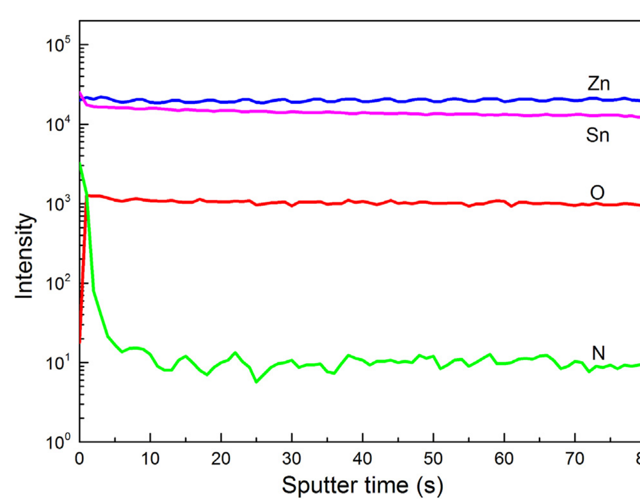


**Fig. 2.** SIMS profile of the ZTO: N thin film.

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