Improved Field Effect Mobility and Stability of Indium-free Oxide Thin Film Transistor by Metal Capping Layer

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ABSTRACT

In this work, to get better electrical properties, metal capping layer and lift-off lithography process of a new type of Indium-free amorphous thin films and associated thin-film transistors (TFTs) were investigated. As a result, optimized TFTs showed high mobility (>30cm^2/Vs) and excellent stability than conventional InZnO TFTs.

1 INTRODUCTION

Since the introduction of the In-Ga-Zn-O (IGZO) TFTs, amorphous oxide semiconductors (AOSs) have attracted considerable attention due to its high field-effect mobility (>10cm^2/Vs), low-temperature fabrication and large area uniformity.[1] However, many studies on AOSs have reported that there is trade-off relationship between electrical performance and device stability, where the mobility increases as a function of In or Sn content, while the stability is degraded simultaneously.[2] Also, because the indium is a rare metal and expensive, using indium is one of critical reasons for increasing overall process costs. Therefore, it is crucial to develop a new novel amorphous In-free oxide semiconductor with high mobility and stability.

In this regard, $(Zn_{1-x}Ba_x)SnO_3$ (ZBTO) has been reported to be a very stable material with high mobility because of its less defective structure and small effective mass [3]. Based on these material characteristics, it is necessary to adopt low cost fabrication processes for TFTs. To fabricate TFTs, many patterning process such as shadow mask, etching lithography and lift-off lithography are commonly used. Among them, lift-off lithography provides a cost effective patterning tool for TFTs devices without the use of sophisticated instruments. Also, it produces device properties with high spatial precision, which is suitable for the fabrication of micrometer-scale devices.

In this work, to fabricate TFTs with high mobility as well as good stability, In-free amorphous ZBTO semiconductor is proposed as a channel layer of TFTs. ZBTO films were fabricated by co-sputtering system using ZTO and BTO target. For comparison, conventional InZnO (IZO) TFTs with similar mobility were also fabricated. ZBTO thin-films and associated thin film transistors were evaluated by changing annealing temperature, annealing ambient, and deposition condition. Also, to further increase the field effect mobility, metal capping layer onto ZBTO layer was introduced. Thermal oxidation of metal layer causes the oxygen deficiency of active layer, which leads to the highly conductive layer. As a result, optimized ZBTO TFTs exhibited high field-effect mobility (>30cm^2/Vs) and excellent bias and illumination stability.

2 EXPERIMENT

A thermally grown 100 nm-thick SiO_x gate insulator was grown onto a heavily doped p-type Si substrates. A 20 nm-thick ZBTO channel layer was deposited by RF magnetron sputtering system. The working pressure was 3 mTorr, and the gas flow rate ratio was Ar:O_2 = 10:0.1. After thermal annealing at 350 °C for 1 hour in air ambient, the 10/150 nm-thick Ti/Al source/drain electrodes were deposited by thermal evaporation process. Channel and source/drain electrode were patterned through lithography and lift-off process, and the channel width and length were 100 μm and 50 μm, respectively. For device with metal capping layer, a 20 nm-thick Ti film was selectively deposited via dc sputtering onto the ZBTO film between the source and drain electrode. And final post-deposition annealing (PDA) was performed at 300 °C for 1 hour in air ambient. The transfer parameters such as threshold voltage, field-effect mobility and subthreshold swing were extracted following gradual channel approximation. The TFT characteristics were measured using HP 4156B semiconductor parameter analyzer.

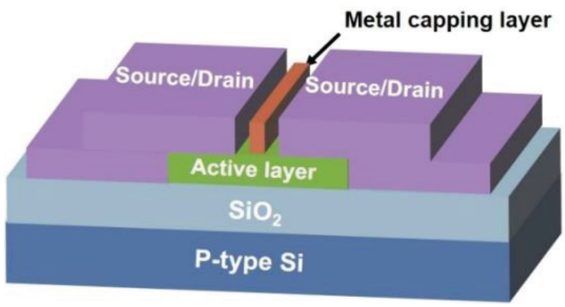

Figure 1. Schematic cross-section of IZO and ZBTO TFTs.

3 RESULTS AND DISCUSSION

X-ray diffraction (XRD) patterns of the ZBTO and IZO thin-films onto glass substrates are shown in figure 1. It indicate that only halo peak in the XRD patterns can be attributed to the glass substrate, which means that the ZBTO and IZO films have an amorphous structure.

To better understand the ZBTO and IZO film microstructure, an atomic force microscopy (AFM) image describing the surface morphology of thin films is presented in figure 2. There are no apparent grain and grain boundaries. The root-mean-square (RMS) roughness of the IZO and ZBTO films were 0.07nm and 0.1 nm, respectively. The smooth surface could effectively suppress the formation of interface charge traps, thus achieving a high mobility and improving the performance of TFTs. [4]

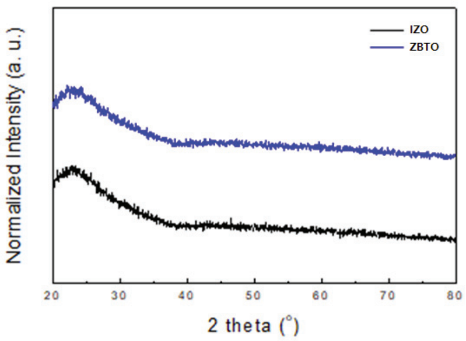

Figure 2. Grazing incidence angle X-ray diffraction (GIAXRD) patterns of ZBTO and IZO thin-films onto glass substrates

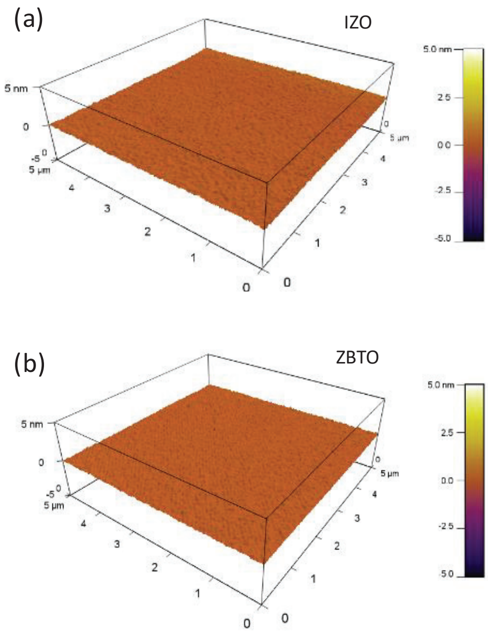

Figure 3. Atomic force microscopy (AFM) images of the surface of (a) IZO and (b) ZBTO films

Figure 3 shows the optical transmittance of the ZBTO and IZO thin-films deposited onto glass substrate. As shown in figure, the optical transmittance of the ZBTO and IZO films is in the range of 80-90 % in visible light range (400-800nm). The optical band gap energy (E_g) value of ZBTO and IZO films was estimated from the inset in figure 3, which was done by extrapolating the linear part of hν versus $(\alpha h\nu)^2$ curve and x-axis of the plot according to Tauc equation. The E_g value of ZBTO and IZO thin film was estimated at 3.47 and 3.24 eV, which show similar values in both films. The optical properties of ZBTO and IZO films indicated high average transmittance above 80%, which is suitable to fabricate transparent thin film transistors.

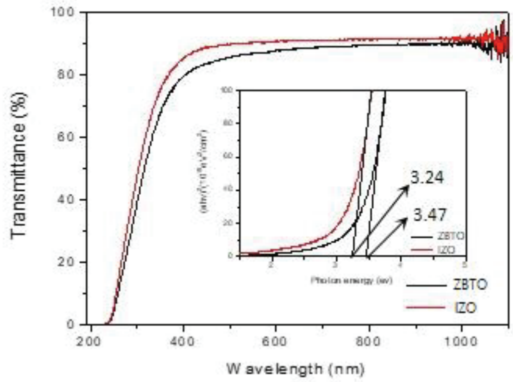

Figure 3. Optical properties of ZBTO and IZO thin-films deposited at room temperature onto glass substrates.

Figure 4 shows the transfer curves of ZBTO, ZBTO with metal capping layer and IZO TFTs, and the representative transfer parameters are listed in table 1. The ZBTO and IZO TFTs represent the similar electrical performance with high mobility above 30 cm^2/Vs. In addition, when comparing the other transfer parameters, ZBTO TFTs shows superior transfer characteristics with small subthreshold swing value and close to zero threshold voltage values than conventional IZO TFTs. Because the subgap (such as oxygen deficiency) and conduction band tail states of ZBTO films were reduced by effect of Ba, ZBTO TFTs show superior electrical properties.[3] Moreover, the ZBTO TFTs with metal capping layer shows improved transfer characteristics with a field effect mobility of 46.52 cm^2/Vs. The weak bond oxygen species in ZBTO film would preferentially be eliminated during formation of TiO_2. Also, thermal oxidation of metal layer causes the oxygen deficiency of active layer. [5] The removal of carrier scattering center and formation highly conductive layer can result in the enhanced field effect mobility.

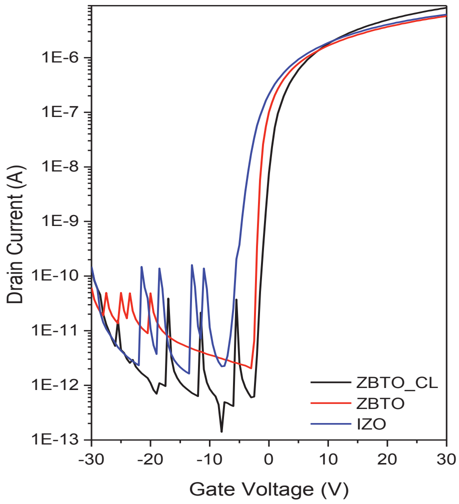

Figure 4. Transfer curves of ZBTO, ZBTO with metal capping layer and IZO TFTs.

Table 1. Representative transfer parameters of ZBTO, ZBTO with metal capping layer and IZO TFTs.

	μ_{FE} (cm^2/Vs)	S.S. (V/dec)	V_{th} (V)
IZO	31.44	0.56	- 4.22
ZBTO	30.26	0.29	- 2.12
ZBTO with CL	46.52	0.41	- 0.89

The stability of the ZBTO, ZBTO with capping layer and IZO TFTs was investigated under negative bias stress (NBS), positive bias stress (PBS) and negative bias illumination stress (NBIS). The bias stress condition is V_G= - 20 V (NBS, NBIS), 20 V (PBS) and drain voltage is fixed at 0.1 V. The illumination for NBIS is 3,000 lx. Figure 5 shows each stability test results of ZBTO, ZBTO with capping layer and IZO TFTs after an hour. All the stability test results of ZBTO TFTs show superior to IZO TFTs. In NBIS test, the light radiation is expected inducing free carriers by peroxide (O_2^{2-}) formation in the donor like valence band tail states caused by structural disordering [6]. Due to the suppressed subgap and valance band tail states of ZBTO films, ZBTO TFTs shows superior NBIS stability than IZO TFTs. [3] For ZBTO TFTs with capping layer, the removal of disorder defects via the metal capping reaction can result in more improved stability under bias and illumination stress. Also, the passivation effect (TiO_2) of the back channel region is one of the origin of their superior electrical stability.

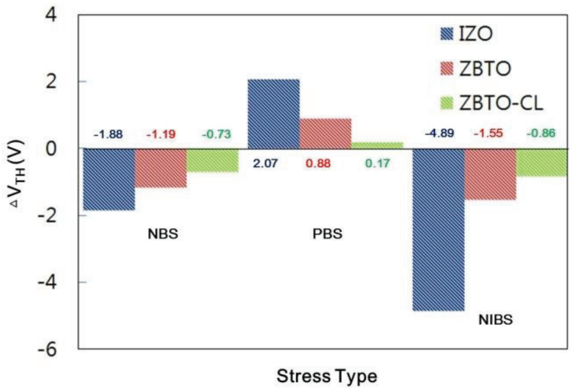

Figure 5. ΔV_{TH} values of ZBTO, ZBTO with capping layer and IZO TFTs under NBS, PBS and NBIS tests as a function of stress time

4 CONCLUSIONS

In this study, to fabricate TFTs with high mobility as well as high stability, ZBTO with metal capping layer is proposed as a cost effective In-free oxide semiconductor. ZBTO and IZO thin-films were fabricated by RF magnetron sputtering method using ceramic targets. Lift-off lithography was used for patterning processes because it is cost effective and exhibits high spatial precision. All films have an amorphous phase structure, smooth surface and the average transmittance exceed 85% in the visible light range. The bias and illumination stability of ZBTO TFTs were superior to those of IZO TFTs. Moreover, due to reduction of disordered defect states and the passivation effect, ZBTO TFTs with metal capping layer showed improved stabilities. In addition, ZBTO TFTs exhibited good electrical properties such as field-effect mobility over 30 cm^2/Vs. These results demonstrate that In-free ZBTO semiconductor will be a promising material of high mobility (≥30 cm^2/Vs) TFTs for next generation display applications.

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