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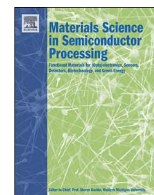

Investigations on the reasons for degradation of zinc tin oxide thin film transistor on exposure to air

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ABSTRACT

Amorphous zinc tin oxide thin film transistor (ZTO TFT) was fabricated in the inverted-staggered (top contact) structure on Si/SiO_2 substrate. The on-off ratio and sub-threshold swing were 2.55×10^6 and 2.3 V/dec respectively. The comparison of transfer characteristics of as prepared and 20 days air exposed ZTO TFT indicates that the threshold voltage and sub-threshold slope are highly influenced by ambient conditions. After exposure to air the device parameters such as μ_{sat}, V_T and SS changed from 0.44 cm^2/V s to 0.49 cm^2/V s, 15 V to 18.5V and 2.3 V/dec to 9 V/dec respectively. The positive shift in threshold voltage can be due to the adsorption of oxygen molecules on the backchannel. The increase in sub-threshold swing after air exposure suggests acceptor like trap creation in the channel layer caused by adsorption of water molecules. The deposition of passivation layer on top of the device reduces the aging effect hence stability of device under ambient condition was improved. Density of states (DOS) of as prepared and 20 days air exposed TFT has been investigated for both passivated and unpassivated devices. Comparison of DOS for the TFTs suggested the formation of large number of trap levels in the ZTO channel layer by water adsorption and it was reduced by the passivation of channel layer of ZTO device.

1. Introduction

Amorphous oxide transparent semiconductors (AOS) are specially attractive materials for the reason that they require a low processing temperature and can be grown on flexible plastic substrates [1]. The display industry is mainly based on thin film transistors (TFTs) made of the conventional materials like amorphous hydrogenated silicon and polycrystalline silicon. In the near future they can be replaced by high potential AOS-based thin film transistors (TFT) [2]. At present indium gallium zinc oxide, zinc tin oxide, zinc indium oxide, zinc indium tin oxide etc are the most used channel materials for the fabrication of AOS- based TFTs [3–7]. Indium free systems are highly preferred for their cost effectiveness. Hence among the above mentioned materials zinc tin oxide (ZTO) is more favourable and economical for fabricating high performance TFT. A field effect mobility as high as 50 $cm^2 V^{-1} s^{-1}$ and on-off ratio 10^7 has been reported for ZTO TFT [8].

Although the mobility is superior to amorphous silicon, the environmental conditions detrimentally affect ZTO device parameters. While considering the commercialization of AOS TFTs, the reliability and stability of such devices are the important factors. In recent years major studies have been focused on the stability of AOS TFTs under various aging parameters and stress conditions [9–11]. It is reported that the adsorbed oxygen captures electrons from the conduction band of the channel layer and creates a depletion region in the backchannel which in turn increases the threshold voltage of TFTs [12]. The deviation of device performance with respect to different ambient conditions arises due to the creation of localised defects in the active channel layer. For instance, in the ambient condition the water vapor adsorption creates large number of deep acceptor like trap levels in the bandgap region of ZTO channel layer and consequently deteriorates the subthreshold swing [13]. One of the most effective ways to reduce the ambient instability of TFTs is to apply a passivation layer onto the device [14].

The correlation between the stability and density of states (DOS) is an important aspect regarding the reliability of AOS material based devices because it contains large number of localized defect states in the bandgap. The exploration of DOS inside the channel layer with and without passivation layer under aging conditions was the main objective of this work. The distribution of those defect states can be examined from the temperature dependent transfer characteristics of TFTs under different aging conditions. Generally, modified variable range hopping (VRH) and multiple trapping and thermal release (MTR) models were used for the calculation of DOS in the bandgap of AOS channel layers [15,16]. In the present study, the device stability with

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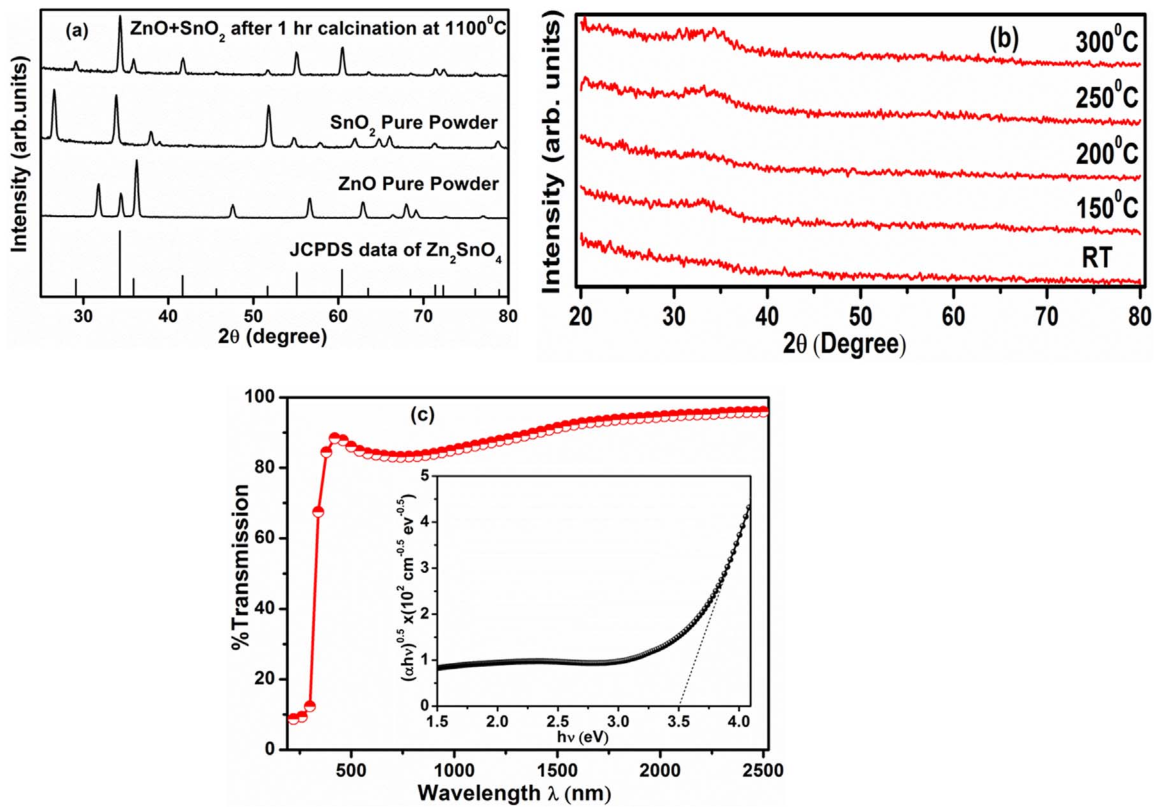

Fig. 1. (a) XRD spectra of ZnO, SnO_2 and ZTO powders (b) XRD of ZTO thin films annealed at different temperatures (c) Transmission spectrum of ZTO thin films annealed at 300 °C. Inset shows the Tauc plot.

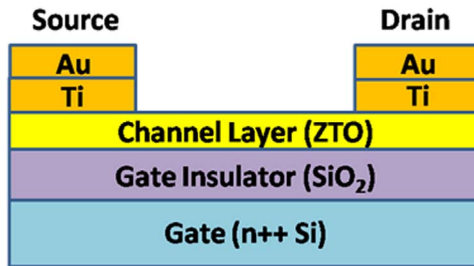

Fig. 2. Schematic cross-section of ZTO thin film transistor.

respect to ambient parameters is well studied by analyzing the variation of DOS in the active ZTO channel layer by MTR model.

2. Device fabrication

Zinc tin oxide (Zn_2SnO_4) thin films were deposited via RF magnetron sputtering using ZTO powder target. Generally ZnO-SnO_2 system has two stable phases: Zn_2SnO_4 and $ZnSnO_3$. For the preparation of phase pure ZTO powder, ZnO and SnO_2 powders were mixed in 2:1 ratio and calcined at 1100 °C for 1 h. All other compositions and calcination temperatures resulted in the formation of either $ZnSnO_3$ phase or a mixture of Zn_2SnO_4, SnO_2 and ZnO phases. The Zn_2SnO_4 has a spinel structure and is chemically and thermally highly stable. Fig. 1 shows the XRD spectra of ZnO, SnO_2 and ZTO powders. The observed XRD data of ZTO powder exactly matches with the JCPDS data (JCPDS No. 24-1470) of cubic spinel phase and no peaks corresponding to any secondary phases were detected.

During sputtering the base pressure and working pressure were 7×10^{-6} and 5×10^{-3} mbar respectively. Fig. 1(b) shows the XRD spectra of as deposited and post annealed ZTO thin films. All the films were amorphous in nature even after post annealing at 300 °C. The optical and electrical properties of the ZTO thin films were studied before TFT fabrication. The films were highly transparent, with an average transmittance of 85% in the visible region (Fig. 1(c)). From the Tauc plot shown in the inset of Fig. 1(c) the bandgap of the film was calculated as 3.5 eV. The carrier concentration and mobility of the as deposited films were 10^{14} cm^{-3} and 1 cm^2 V^{-1} s^{-1} respectively. On post deposition annealing at 300 °C for 1 h under ambient conditions, the carrier concentration and mobility values increased to 10^{16} cm^{-3} and 5 cm^2 V^{-1} s^{-1} respectively. The observed optical and electrical parameters of the ZTO thin films were comparable to those of ZTO thin films prepared by PLD and sputtering [17,18].

The n-type amorphous ZTO TFTs with and without passivation layer were fabricated in the inverted-staggered (top contact) structure as shown in Fig. 2. Heavily doped n-type silicon wafer was used as the gate electrode, with 100-nm of thermally grown silicon dioxide serving as the gate dielectric. By making use of a shadow mask, patterned ZTO channel layer was deposited on silicon dioxide layer. After deposition, the channel layer was annealed at 300 °C for 1 h under ambient conditions. Shadow mask was used to deposit Ti (10 nm)/Au (100 nm) source-drain contacts thereby defining the channel length and width as 65 and 1000 µm respectively. In this type of unpassivated TFT, the back channel is exposed to the environment, which will adversely affect the performance and long term stability of the device. To overcome these concerns titanium oxide (TiO_2) passivation layer of 100 nm thickness was deposited by RF sputtering on the top of the device. The passivated and unpasssivated devices were exposed to air for 20 days and the transfer characteristics were measured to study the aging effect.

The output characteristics of TFT are similar to those of MOSFET [7]. The drain current can be expressed by the relations:

$$I_D = \mu C_i \frac{W}{L}\left[(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right], \text{for} V_{DS} \le V_{GS} - V_T \quad (1)$$

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