Characterization of E-Mode InZnO Thin Film Transistors Produced by DC Sputtering Technique

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In this work, InZnO and InGaZnO were used as channel layers to fabricate enhancement mode thin film transistors on glass and flexible transparent substrate. The SiO_2-In_2O_3-ZnO system and N_2 plasma incorporated IZO film were grown to get a better controllability of the carrier concentration during the film growth. Hydrogen plasma and oxygen plasma effects on the TCO films and the TFTs were investigated.

Keywords: Thin Film Transistor, InZnO films, DC sputtering, ZnO devices
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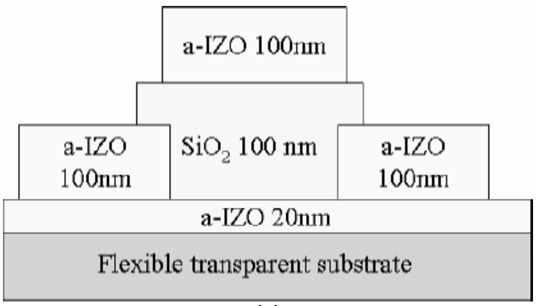
1. Introduction

Transparent conductive oxides (TCOs) were applied in many areas, such as the transparent electrodes used in liquid crystal displays, solar cells, and light emitting diodes because of their high electrical conductivity and high optical transparency [1-3]. Oxide-based thin film transistors attract much attention due to their advantages such as high mobility, high electrical conductivity, and high visible transmittance [4-7]. Amorphous or nano-crystalline n-type oxide semiconductors such as zinc oxide, zinc tin oxide, indium gallium oxide, and indium gallium zinc tin oxide displays demonstrate surprisingly high carrier mobilities (~10cm^2/Vs) even for amorphous films deposited at room temperature [8-11]. Many transparent thin film transistors (TTFTs) were reported using crystalline ZnO [12,13], or polycrystalline SnO_2 [14], and In_2O_3 [15]. However, to realize the transparent thin film transistor for flexible electronics, amorphous films are more suitable than crystalline type, because amorphous type oxide films have extra advantages such as low temperature deposition, good film smoothness, low compressive stress, and large area deposition by sputtering [16-18].

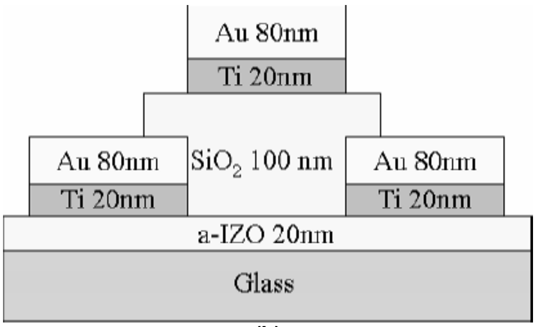
Among various conductive oxides, the IZO system exhibits many advantages for the flexible transparent TFTs such as high field effect mobility, high transparency, room temperature compatible process, large area deposition by sputtering, plastic substrates available, and is a cheaper process [6,20,22]. Other conductive oxides may not fit all the requirements for the flexible transparent TFTs. The first requirement is the film has to be transparent in visible region which means the bandgap E_g>3eV. CdO-PbO and $AgSbO_3$ systems have a bandgap smaller than this requirement [23,24]. The second requirement is the film must be amorphous and conductive as deposited in room temperature. CdO-CeO_2 is very resistive (resistivity ~1x10^{4}Ω.cm) [25] as deposited if no dopants are added in. In addition, Cd^{2+} ions is toxic against the environment [26]. Amorphous In_2O_3 looks like a good candidate, however, when the oxygen ratio increases a little bit, it becomes polycrystalline [27]. ZnO is always polycrystalline as deposited [22]. In_2O_3-ZnO systems have a wide range of amorphous materials in In/Zn ratio and various oxygen partial pressure [21,26]. Note that the change in oxygen ratio is very important because the carrier concentration can be adjusted by controlling the oxygen partial pressure or the O_2/Ar ratio. α-IZO has a considerable high mobility (10~50 cm^2/Vs) [22,28] as deposited at room temperature which is at least one order higher than amorphous Si [28]. Ga_2O_3-ZnO (GZO) system has a little bit lower mobility than IZO [22]. GaInZnO (GIZO) also has a little bit lower mobility compared to IZO [26]. The last candidate is ITO, which is widely used as electrodes in LEDs, solar cells and LCDs [29-31]. Compared to ITO, IZO has a higher work function [32,33], higher transmittance in the infrared region [34], and lower In concentration than ITO. A higher In concentration means higher price [33]. Accordingly, the IZO will be used as channels and electrodes to fabricate the flexible transparent TFTs in this research. GIZO-TFTs were reported having a better stability than IZO-TFTs [35]. Thus, GIZO-TFTs will also be included in this study.

2. Experiment

The enhance mode TFT structure is shown in Fig. (1a). We also plan to use IZO and IGZO as the channel layers and design structures for the channel. Recently, we successfully fabricated enhance mode thin film transistors using IZO as the channel layer as depicted in Fig. (1b). The device has very good performance which will be described later.



(a)



(b)

Fig. (1) (a) Schematics of the E-Mode TFTs on flexible transparent substrate and (b) E-Mode TFTs on glass

The IZO film was deposited in the sputtering machine with two targets, ZnO and In_2O_3, together with O_2 and Ar gas in the chamber. The O_2/Ar ratio decides the carrier concentration in the IZO film. Here we plan to use N_2/O_2/Ar gas mixture to deposit IZO film. The reasons to use N_2 is because in the plasma, N_2 will convert to N_2^+, which may replace O and bond with In. This was investigated in forming p-type ZnO [36]. We know the carriers in the IZO result from the non-stoichiometry, which means the lack of oxygen allows some In atoms that are not bonded with oxygen atoms to release electrons to the conduction band. That is why when the O_2/Ar ratio change during IZO film deposition, the carrier concentration will also change. Higher O_2/Ar ratio leads to a decrease in the number of oxygen vacancies, which also means the carrier concentration decreases [21]. When removing one oxygen atom from the indium, one oxygen vacancy is created. Indium is a big atom and tends to lose electrons. Oxygen is a small atom and tends to get electrons from the indium. ZnO acts as a stabilizer in the In_2O_3 matrix. That's why IZO and (GaZnO) GZO both have lower sensitivity of O_2/Ar ratio to carrier concentration than ZnO [22]. Since the oxygen has a higher electronegativity than nitrogen, oxygen can form a strong ionic bond with indium. This means when removing or adding a certain amount of oxygen or nitrogen bonded with indium, oxygen will produce a larger change in carrier concentration than nitrogen. This means nitrogen can reduce the sensitivity of O_2/Ar ratio to carrier concentration. The second reason is, due to the previous reason, nitrogen may improve the device reliability. A reliability issue is one of the reasons why GaInZnO was developed [35]. We may provide another view to do the same thing by an easier method.

Ga_2O_3 introduced into the In_2O_3-ZnO system to form the InGaZnO was reported as providing a better stabilization in TFTs than IZO [35]. Gallium was chosen because it has an atomic radius close to indium. The introduction of gallium into the IZO reduces the electron concentration and mobility. The highest carrier concentration of IGZO is around $\sim 10^{19} cm^{-3}$ [26] which is smaller than that of IZO ($\sim 10^{21} cm^{-3}$) [19,22]. The reduction in carrier concentration is not bad because for the channel layer, $10^{18} \sim 10^{16} cm^{-3}$ is enough for both depletion and enhancement mode TFTs. Although carrier concentration in IZO can also be adjusted by O_2/Ar ratio, the carrier concentration change in the IZO film is dramatic ranging from 10^{18} to $10^{16} cm^{-3}$ in a small O_2/Ar ratio region [21]. Gallium not only reduces carrier concentration, but also reduces the sensitivity of the carrier concentration to the O_2/Ar ratio [22,26]. It is good for controlling the carrier concentration. However, in the mean time, the reduction in mobility is not desired. It is interesting to introduce another oxide into the IZO system to stabilize the oxide system and the mobility. The idea is to incorporate a smaller atom and in the mean time, oxide formed by this atom has E_g>3eV. SiO_2 fits these requirements. Si can easily bond with oxygen to reduce sensitivity of the carrier concentration to the O_2/Ar ratio during film deposition. Also, due to the smaller radius of Si than Ga, In atoms still can keep their s orbitals overlapped. This means the mobility may not be degraded too much.

Due to the different interfaces that may form between IZO and various dielectrics, it is necessary to use different dielectrics such as SiO_2, SiN, and Sc_2O_3 as the gate dielectrics in the TFTs and compare the device performance.

O_2 plasma can obviously decrease the surface carrier concentration of the IZO film due to the annihilation of the oxygen vacancies. This might help to reduce the surface leakage and then improve on/off ratio if the surface leakage dominates the leakage current, especially for the depletion mode FET.

After we successfully fabricate the E-mode FETs, we can start to make a ring oscillator using these TFTs. The reliability test will include (i) current stress in room temperature and high temperature (ii) thermal shock and bending test. These tests will be applied to the TCO films and devices on both glass and PET. The device will also be measured for the s parameters and be simulated to extract the parasitic parameters of the D-mode and E-mode FETs. We have already performed the simulation for the D-mode IZO TFTs.

3. Results and Discussion

Enhancement mode top-gate TFTs using 20nm of *a*-IZO channels and 100nm thick SiO_2 gate insulators deposited by plasma-enhanced chemical vapor deposit ion (PECVD) were fabricated. Figure (1b) shows the cross-section structure of the TFT with a gate dimension of 1μm×100μm. The IZO film was deposited in 3.1% of O_2/Ar ratio has a carrier concentration about $1.5x10^{16}cm^{-3}$. The SiO_2 layer was deposited without heating the substrates, making the entire process consistent with typical continuous-use temperatures of commercial plastic films for electronic devices.

Figure (2) shows typical drain current versus drain voltage, I_{DS}-V_{DS}, characteristics from the IZO transistors. The transistor operates in enhancement-mode showing excellent pinch-off.

Figure (3) shows drain current, I_{DS}, and transconductance, g_m, as a function of V_{GS} for an IZO TFT. A transconductance of 10mS/mm was obtained at drain current of 0.3mA at 0.85V gate voltage and 3V drain voltage. The transistor has a low threshold voltage of 0.5V and an excellent sub-threshold voltage swing of 0.135V/decade. The drain current on-to-off ratio was $\sim 10^5$. The gate leakage is about 10^{-10}~10^{-9}A.

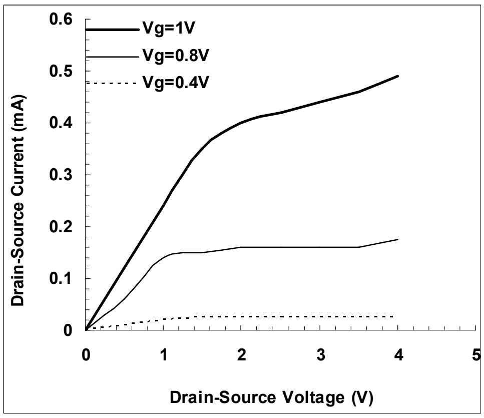


Fig. (2) Typical drain current versus drain voltage, I_{DS}-V_{DS}, characteristics from the IZO transistors

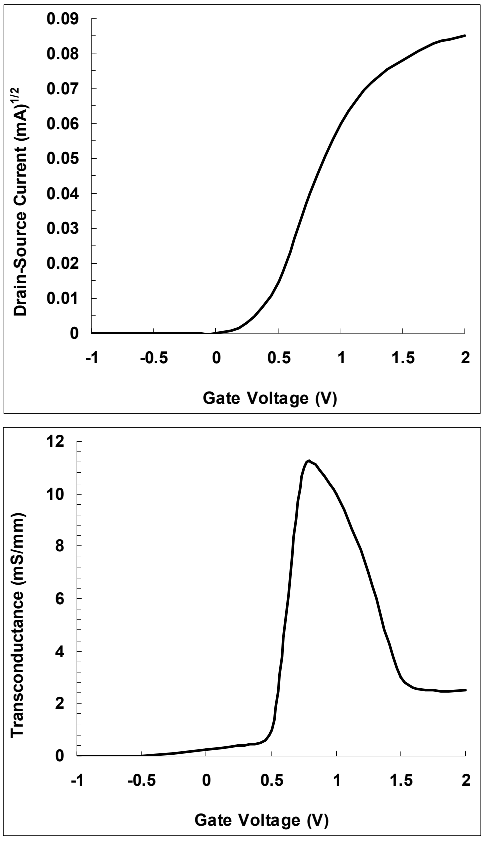


Fig. (3) Drain current, I_{DS}, and transconductance, g_m, as a function of V_{GS} for an IZO TFT

4. Conclusion

In this work, IZO and IGZO were used as channel layers to fabricate enhancement mode TFTs and ring oscillators on glass and flexible transparent substrate (PET). The SiO_2-In_2O_3-ZnO system and N_2 plasma incorporated IZO film were grown to get a better controllability of the carrier concentration during the film growth. Hydrogen plasma and oxygen plasma effects on the TCO films and the TFTs were investigated. The device reliability was tested to compare the effects from different TCO films and process treatments. Devices were simulated in a device model to extract the parasitic parameters.

Devices were characterized in dc and rf performance. The enhancement mode TFTs have been fabricated successfully on glass by using IZO films as the channel layers.

References

[1] A.K. Kullarni et al., *Thin Solid Films*, 308 (1997) 1.
[2] K. Zhang et al., *Thin Solid Films*, 376, 255, (2000).
[3] H. Kim et al., *J. Appl. Phys.*, 86, 6451 (1999).
[4] K. Nomura et al., *Nature*, 432, 288 (2004).
[5] E. Fortunato et al., *Appl. Phys. Lett.*, 85, 2541 (2004).
[6] N.L. Dehuff et al., *J. Appl. Phys.*, 97, 064505 (2005).
[7] E. Fortunato et al., *Adv. Mater.*, 17 590 (2005).
[8] J. Park et al., *J. Vac. Sci. Technol.*, B24, 2737 (2006).
[9] H.-H. Hsieh and C.-C. Wu, *Appl. Phys. Lett.*, 89, 041109 (2006).
[10] J. Siddiqui et al., *Appl. Phys. Lett.*, 88, 212903 (2006).
[11] P.F. Garcia, R.S. McLean and M.H. Reilly, *Appl. Phys. Lett.*, 88, 123509 (2006).
[12] P.F. Carcia et al., *Appl. Phys. Lett.*, 82, 1117 (2003).
[13] E. Fortunato et al., *J. Non-Cryst. Solids*, 338-340, 806 (2004).
[14] R.E. Presley et al., *J. Phys. D: Appl. Phys.,* 37, 2810 (2004).
[15] Dhananjay, C.W. Chu, *Appl. Phys. Lett.*, 91, 132111 (2007).
[16] H. Yabuta et al., *Appl. Phys. Lett.*, 89, 112123 (2006)
[17] T. Minami, *J. Vac. Sci. Technol.*, A17 (1999) 1765.
[18] T. Sasabayashi et al., *Thin Solid Films*, 445, 219 (2003).
[19] H.C. Pan et al., *J. Vac. Sci. Technol.,* A 23, 1187 (2005).
[20] Yu-Lin Wang et al., *Appl. Phys. Lett.*, 90, 1 (2007)
[21] W. Lim et al., *Electrochem. Solid-State Lett.*, 10, H267 (2007).
[22] R. Martins et al., *J. Appl. Phys.*, 101,044505 (2007).
[23] H. Hosono et al., *Appl. Phys. Lett.*, 68,29 (1996).
[24] M. Yasukawa et al., *Jpn. J. Appl. Phys.*, Part 2, 34, L281 (1995).
[25] S. Narushima et al., *J. Non-Cryst. Solids*, 374, 313 (2000).
[26] H. Hosono, *J. Non-Cryst. Solids*, 352, 851 (2006)
[27] H. Nakazawa et al., *J. Appl. Phys.*, 100, 093706 (2006)
[28] Y. Sun and J.A. Rogers, *Adv. Mater.*, 19, 1897 (2007).
[29] H. Fujikawa et al., *Appl. Phys. Lett.*, 70, 270 (1997).
[30] L. Davis, *Thin Solid Films*, 236,1 (1993).
[31] F. Benkhelifa et al., *Thin Solid Films*, 232, 83 (1993).
[32] J. Cui et al., *Adv. Mater.*, 31, 1476 (2001).
[33] B. Kumar and H. Gong, *J. Appl. Phys.*, 98, 073703 (2005).
[34] J.M. Philips et al., *Appl. Phys. Lett.*, 67, 2246 (1995).
[35] T. Kamiya et al., *J. Electroceram.*, 17,267 (2006).
[36] C.L. Perkins et al., *J. Appl. Phys.*, 97, 034907 (2005).