High mobility zinc oxynitride-TFT with operation stability under light-illuminated bias-stress conditions for large area and high resolution display applications

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Introduction: In spite of the successful achievement of oxide-semiconductor (OS) technology in recent years, stability degradation especially at high mobility regime limits the application of oxide semiconductors in next generation displays. According to previous works, the instability is closely related to oxygen vacancies (V_o) causing persistent photoconductivity (PPC) [1,2]. From this point of view, zinc oxynitride (ZnON)[3] with small bandgap (1.3 eV) and high intrinsic mobility is attractive to overcome the performance issues of OS. In this paper, we report on ZnON-thin film transistors (TFTs) with field effect mobility near 100 cm^2/Vs and operation stability(< 3 V) under light-illumination bias-stress. Our results demonstrate that ZnON-TFTs are strong candidates for pixel switching devices in ultra-high definition and large area displays.

ZnON film deposition and electrical properties: ZnON films were deposited by reactive rf magnetron sputtering using Zn target and Ar/O_2/N_2 mixture gas. By varying the O_2 flow rate and deposition pressure at a fixed N_2 and Ar flow rate, the anion ratio (O/N) in ZnON was modulated, while maintaining Zn concentration at ~55 at%. As-deposited and annealed films are composed of amorphous ZnON and nano-crystallites of ZnO and Zn_3N_2 (Fig. 1). Density functional theory (DFT)-based calculations (Fig. 2) revealed that ZnON has a smaller effective mass (0.19 m_e) than conventional OSs (0.27 m_e for ZnO, 0.32~0.34 m_e for GIZO[4], and 0.22 m_e for In_2O_3), indicating high mobility characteristics of ZnON. Hall measurements confirmed its high mobility values of 35~118 cm^2/Vs with carrier concentrations of 7.7×10^{16}~3.1×10^{18} /cm^3 [Fig 3(b) and (c)]. As shown in Fig. 3, N incorporation is directly related with the enhancement of mobility and carrier concentration.

ZnON-TFT fabrication and basic characteristics: We have fabricated etch-stopper (ES) type ZnON-TFTs (N/O=37/6) on 150 mm x 150 mm glass substrates by photolithography and etching processes. After patterning a sputter-deposited Mo layer for gate electrodes, plasma-enhanced chemical vapor deposition (PECVD) was used to deposit gate dielectrics of SiN_x/SiO_x (350 nm/50 nm). ZnON (50 nm) was subsequently sputter-deposited as the active layer. Then, 100 nm-thick PECVD SiO_x was deposited and patterned to form the ES and contact regions. Mo or AlNd source/drain (S/D) electrodes were formed by sputtering and dry etching process. TFT structures are illustrated in Fig. 4. After annealing in air at 250 ^oC for 1 hr, we have measured I-V characteristics, including operation stabilities, in vacuum (<10^{-6} Torr). Fabricated ZnON-TFTs operated in depletion mode. Thus, TFT current includes fringe component. TFTs still have mobility as high as ~100 cm^2/Vs even after fringe current correction by channel width (W) dependent I_{ds}-V_{gs} analysis (Fig. 5). Transfer (I_{ds}-V_{gs}) and output characteristics are given in Fig. 6(a) and (b), respectively. Figure 7 shows areal uniformity of devices with W/L=75 μm/15 μm. The extracted values are 99±6.2 cm^2/Vs for mobility, -4.82±0.39 V for threshold voltage (V_{th}), and 1.02±0.02 V/dec for subthreshold swing (S), respectively. Not only the uniformity is suitable for display applications but also the mobility performance is comparable to that of polysilicon (poly-Si).

Operation stability under light illumination: Figure 8 shows the calculated electronic density of states in ZnON obtained by DFT-based 1st principle calculation. Compared to oxide semiconductors, ZnON has a smaller bandgap (E_g=1.3 eV) which is mainly due to N states in the valence band (VB). This indicates that V_o in ZnON are buried in the VB and thus cannot act as trapping centers for the PPC. Optical absorption spectra of ZnON and InZnO (IZO) in Fig. 9 also show that ZnON band-structure completely covers the peak at 2.3 eV, which is related with deep states such as V_o in OS. Schematic band diagrams of Zn_3N_2, ZnON, and ZnO, given in Fig. 10, which reflect this situation. In Fig. 11, we compare the light response of ZnON and IZO by using TFT at off-region. While IZO shows large photocurrent and significant amount of current still exist after the light is turned off, i.e. PPC phenomenon, ZnON has 1000 times lower photoconductivity and is PPC-free. Thus, the result of Fig. 11 strongly suggests that degradation is suppressed in ZnON TFTs. Figure 12 shows I_{ds}-V_{gs} of ZnON TFT with stress time for negative gate bias. In Fig. 13, ΔV_{th} and mobility of ZnON, GIZO, and IZO-TFT are compared. ΔV_{th} of GIZO and IZO TFT in the dark state is only 0.4 V, however, its value was significantly degraded to -10.1 and -12.8 V under light illumination. Although ZnON TFT has -2.03 V of ΔV_{th} under dark condition (due to its weak p-type character as shown in Fig. 6), it maintains similar level of ΔV_{th} (-2.87 V) under light illumination, owing to the unique characteristics of ZnON as we mentioned above.

Summary and conclusion: We have investigated material and electrical properties of ZnON based on 1st principle calculations and TFT evaluations. Theoretically, ZnON has high mobility characteristics and band-structure for high stability. Fabricated TFTs exhibited high mobility (100 cm^2/Vs), good uniformity, and stable operation performance such as -2.87 V of V_{th}-shift under light illuminated bias-stress condition. As a new approach to overcome the performance limit of oxide-semiconductors, ZnON technology is strongly promising to achieve high mobility and operation stability required for next generation displays.

References : [1] K. Moazzami et al., Semicond. Sci. Technol. 21, 717 (2006). [2] S. H. Jeon et al., Nat. Mater. 11, 301 (2012)]. [3] Y. Ye et al., J. Appl. Phys. 106, 074512 (2009). [4] T. Kamiya et al., Sci. Technol. Adv. Mater. 11 044305 (2010).

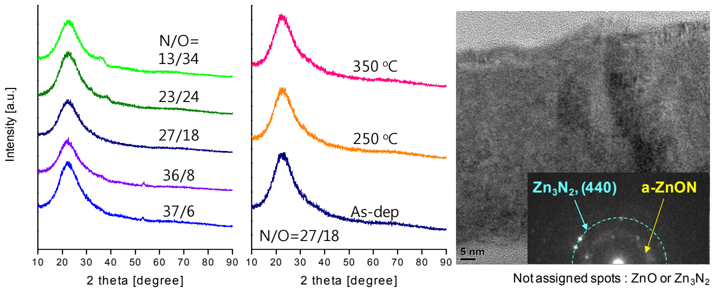
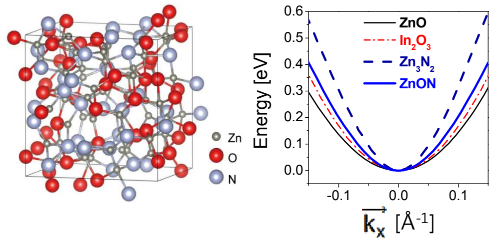


Fig. 1. Microstructures of ZnON films. (a) and (b) are grazing incidence angle X-ray diffraction (GIAXRD) patterns of ZnON films with anion composition and annealing temperature, respectively. (c) Cross-sectional TEM image and diffraction pattern of ZnON film with N/O=37/6.



Material	ZnO	In_2O_3	**a-ZnON**	Zn_3N_2
m_e^* / m_e	0.27	0.22	**0.19**	0.10

Fig. 2. (a) An atomic structure of a-$Zn_{60}O_{24}N_{24}$ formed by melt-and-quench simulation. (b) Conduction bands of c-ZnO, c-In_2O_3, c-Zn_3N_2, and a-ZnON. For comparision, conduction band minima (CBM) were aligned at 0 eV.

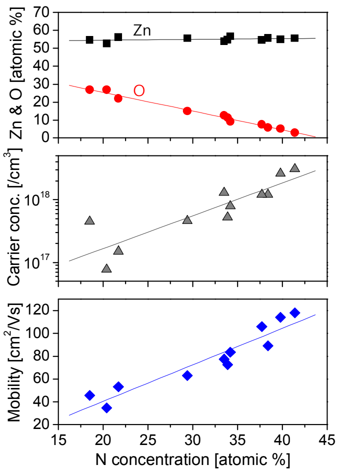


Fig. 3. Film composition and corresponding electrical properties of ZnON as a function of N-concentration. (a) Zn- and O-concentration. (b) and (c) are carrier concentration and mobility from Hall measurements.

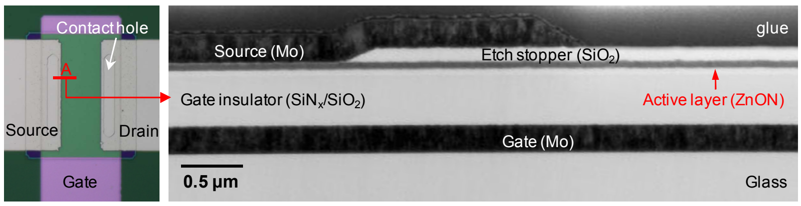


Fig. 4. Structure of ES-type ZnON-TFT fabricated by photolithography. (a) Top view from optical microscope and (b) cross-sectional TEM image at the vicinity of contact region (A).

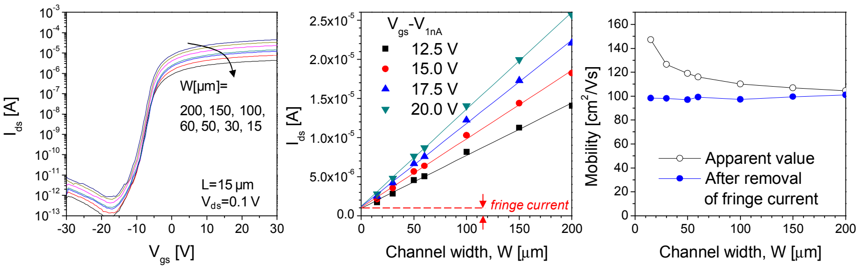
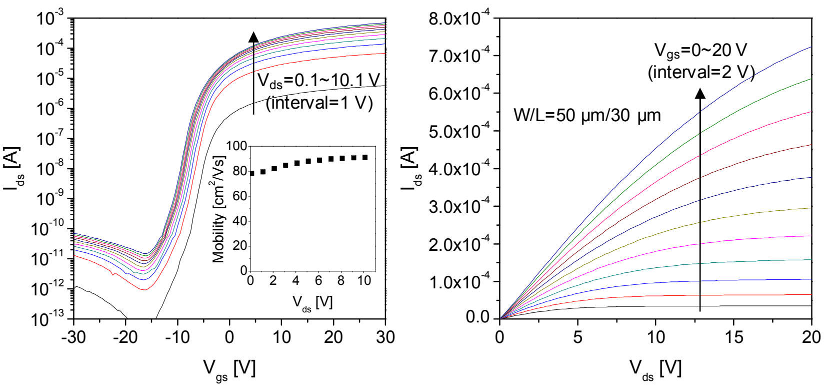


Fig. 5. Actual mobility extraction by fringe current correction. (a) Transfer curve with channel width (W) (b) I_{ds} with W for fringe current evaluation (c) Mobility with W



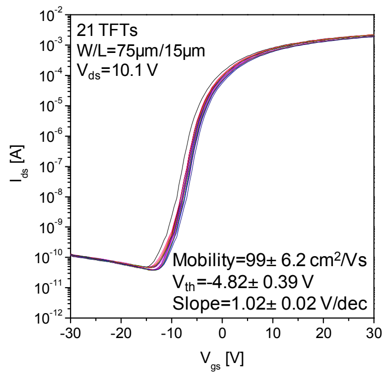


Fig. 6. (a) Transfer (I_{ds}-V_{gs}) (b) output (I_{ds}-V_{ds}) characteristics

Fig. 7. TFT uniformity

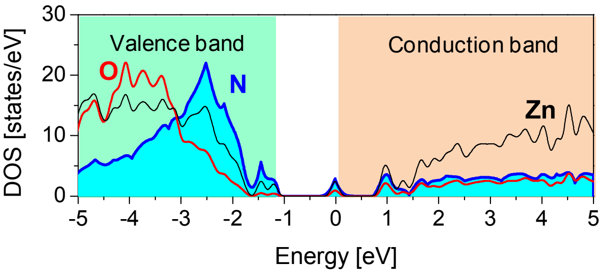


Fig. 8. Calculated electronic density of states (DOS) by using the primitive cell in Fig. 2(a). The CBM energy level is set to 0 eV.

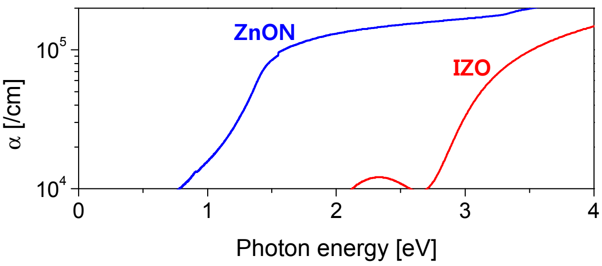


Fig. 9. Absorption coefficient (α) of ZnON and IZO

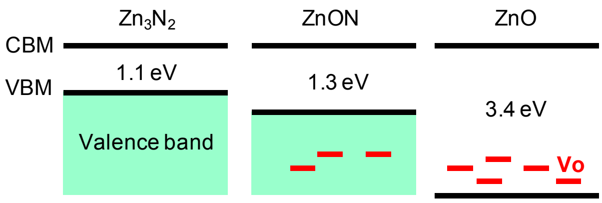


Fig. 10. Schematic band diagram of Zn_3N_2, ZnON, and ZnO

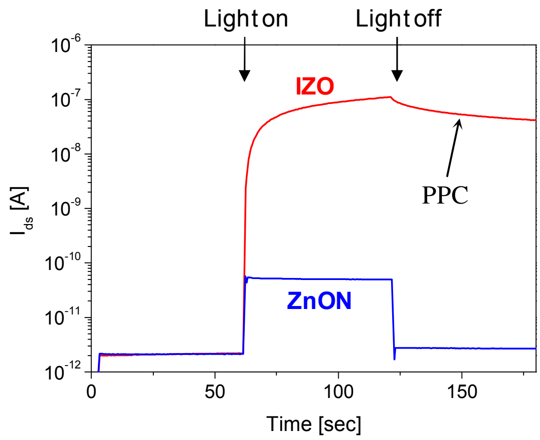


Fig. 11. Photo-response of ZnON and IZO TFTs. (Light source is a white-light LED at a luminance of 15,400 lux)

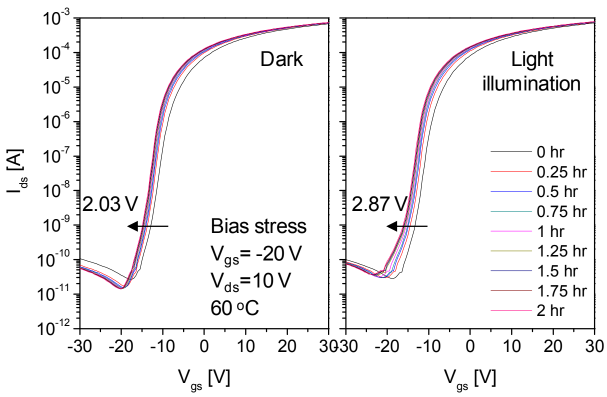


Fig. 12. Operation stability of ZnON-TFT under dark (a) and (b) light illumination (Light is a blue LED at 16 μW/cm^2)

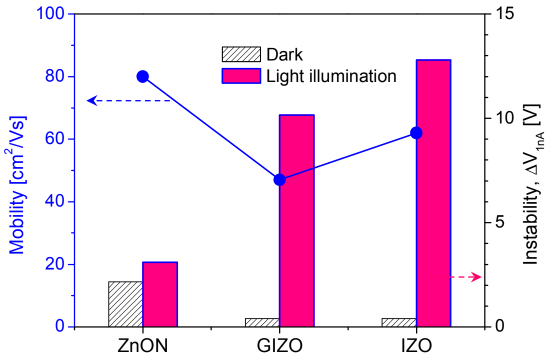


Fig. 13. Comparison of stability under dark and light illumination between ZnON, GIZO and IZO.