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Electrical performance and stability of Tungsten Indium Zinc Oxide Thin-Film Transistors

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Abstract—Amorphous tungsten indium zinc oxide thin film transistors (WIZO TFTs) have been prepared using radio-frequency (RF) magnetron co-sputtering system to co-sputter indium zinc oxide (IZO) and indium tungsten oxide (IWO) targets. The electrical performance parameters and positive biased stress (PBS) test of the co-sputtered WIZO TFT were investigated to obtain better characteristics with regards to the IZO and IWO TFT counterparts. The co-sputtered TFT displayed high electrical performance (field effect mobility, $\mu_{FE} \sim 22.30 \text{ cm}^2/\text{Vs}$, and sub-threshold swing, $SS \sim 0.36 \text{ V/decade}$) and stable electrical behavior (PBS value shift, $\Delta V_{th} \sim 1.23 \text{ V}$) than the IZO ($\mu_{FE} \sim 19.90 \text{ cm}^2/\text{Vs}$, $SS \sim 0.46 \text{ V/decade}$, $\Delta V_{th} \sim 7.79 \text{ V}$) and IWO (conducting in nature) TFTs for its application in flexible and transparent displays.

Keywords — Sputtering, Semiconductor, Thin films.

1. Introduction

Oxide semiconductor thin films can be deposited by various techniques for the realization of thin film

transistors (TFTs) with better device performance, optical transparency, low temperature process, and low

cost fabrication over silicon based TFTs [1, 2]. Among these, AOS materials now become potential

candidate for the development of next generation fully transparent and flexible displays. However, the

long term stability and reliability of AOS TFTs are the utmost issues nowadays [3]. The amorphous

indium gallium zinc oxide (a-IGZO) TFT has now been considered as the most commercialized and suitable candidate for display industries. In IGZO, Ga is used to suppress the charge careers and stabilizing the network. However, the Ga has disadvantage in terms of cost, instability under acidic environment, and scarcity [4]. A very few and limited metals with high dielectric constants (high-k) such as titanium (Ti), tantalum (Ta), hafnium (Hf), zirconium (Zr), etc., have been used to make TiInZnO , TaInZnO , HfInZnO , ZrInZnO , TFTs to solve the instability problems by controlling the oxygen vacancies [4-7]. However, up to now there have been no reports on a-Tungsten Indium Zinc Oxide (WInZnO ; WIZO) TFTs' electrical performance and stability behavior under positive gate biased (PBS) condition. In this paper, we have fabricated TFTs using a Tungsten indium zinc oxide (WIZO) thin film as the active channel layer and investigated their electrical performance and positive gate bias stability.

2. Experimental

IZO, IWO and IZO co-sputtered IWO (WIZO) thin films (thickness ~ 10 nm) were deposited on SiO_2/Si and glass substrates at room temperature using a dual RF magnetron sputtering with $\text{ZnO}:\text{In}_2\text{O}_3$ (a-IZO) (molar ratio of 2:1) and $\text{In}_2\text{O}_3:\text{WO}_3$ (a-IWO) (98:2 wt.%) targets of 99.99% purity. Initially, the co-sputtering system was evacuated to 3×10^{-6} mbar. After that, deposition of IZO and IWO target was carried out with a gas mixing ratio of $\text{Ar} : \text{O}_2 : \text{N}_2$ (28 : 2 : 1.5) and a total chamber pressure of 3 mtorr by RF magnetron sputtering at the RF power of 50 W. All the oxide films were annealed at 300 °C for 30 min in nitrogen environment. Their chemical composition, morphology and optical properties were investigated using X-ray photoelectron spectroscopy (XPS, PHI 5000 versa probe II with monochromatic Al K α radiation, 1486.6 eV), atomic force microscope (Nanoscope SPM V5) and ultraviolet-visible

spectrophotometer (Perkin Elmer lambda 950), respectively. The thin films prepared on SiO₂/Si were employed as an active channel layer, SiO₂ (thickness ~100 nm) as an insulator and Si as a gate for TFTs. ITO source and drain contacts (thickness ~ 50 nm) were sputter deposited (0.27 Å /s) on the active channel layer through a shadow mask by using In₂O₃: SnO₂ (90:10 wt%) target of 99.99% purity. During sputtering, the RF power and argon gas pressure in the chamber were maintained at 50 W, 3 mtorr, respectively. Further, the devices were annealed at 300°C for 30 min in N₂ environment. The measured devices have an electrode width (W) of 400µm and a channel length (L) of 600µm. All electrical characterizations were performed using a semiconductor parameter analyzer (Keithley 4500C) in the dark at room temperature.

3. Results and discussion

The chemical composition of IZO, IWO and WIZO thin films has been investigated by X-ray photoelectron spectroscopic (XPS) study (Table 1). The tungsten (W 4f) spectra of the tungsten containing IZO films consist with doublet peaks (Fig.s1 as supplementary material) observed at 36.2 and 37.8 eV corresponding to 4f^{7/2} and 4f^{5/2}, respectively. It indicates that the tungsten in the film present as

Table 1. Chemical composition of various thin films measured by XPS analysis.

Thin Film	Atomic%				M _{In} = (In)/(In+Zn+W)
	O	In	Zn	W	
IZO (10 nm)	71.93	6.99	21.08	0	0.25
WIZO (10 nm)	79.6	8.94	11.39	0.08	0.44
IWO (10 nm)	86.98	12.92	0	0.11	0.99
M _{In} - Molar indium cation ratio, In-Indium, Zn-Zinc, W-Tungsten, O-Oxygen					

the 6-valent state (W^{6+}) [8]. The surface morphology of IZO films with and without tungsten doping was observed by atomic force microscope (AFM) (Fig.s2 as supplementary material). A small amount of tungsten (0.08 at %) (Table 1) doping in IZO slightly improves the surface roughness; the root mean square roughness (R_{rms}) values being 1.80 and 1.60 Å for IZO and WIZO films, respectively. The ionic radius of tungsten (0.60Å) is comparatively smaller than the indium (0.80Å) and zinc (0.74Å) [9]. It indicates that the tungsten ions can easily enter into the lattice sites of the IZO and slightly improve the surface roughness. However, the small amount of tungsten in IZO greatly influenced the density of tail states or localized states within the band gap (E_g). The density of tail states within the band gap [E_g is deduced from the intercept of $(\alpha h\nu)^2$ versus $h\nu$ plot at abscissa (Fig.1)] is estimated by Urbach's width (ΔE) [10]. The inverse slope of linear plot of $\ln\alpha$ versus $h\nu$ (inset of Fig.1) in tail region (below the band gap, $E_g < 3.55$ eV) gives the value of Urbach's width (ΔE), wherein $\alpha \sim (-[\ln T]/t$; T is the optical transmittance, and t is the film thickness) represents absorption coefficient, $h\nu$ is the incident photon

Fig.1 $(\alpha h\nu)^2$ versus $h\nu$ plots of IZO based thin films annealed at 300°C for 30 min in N_2 environment. The corresponding $\ln(\alpha)$ versus $h\nu$ plots are shown in the inset.

energy. The value of Urbach's width for WIZO ($\Delta E \sim 530$ meV) is lower than IZO film ($\Delta E \sim 640$ meV), indicating lower density of localized states within the band gap of tungsten containing IZO (WIZO) films.

The tungsten incorporation in IZO, thus, improves the film quality to be utilized for fabricating better

TFTs. To examine the effect of tungsten on electrical performance and stability of IZO TFTs, various

TFTs such as IZO, IWO, and WIZO have been fabricated and characterized. Transfer characteristics

(Figs. 2(a-c)) of IZO, IWO and IZO co-sputtered IWO (WIZO) TFTs are performed to extract the

threshold voltage (V_{th}), sub-threshold swing (SS) and linear field effect mobility (μ_{FE}) (Table 2). The

indium tungsten oxide (IWO) TFT was in ON-state due to high molar cation ratio of indium ($M_{In} \sim 0.99$)

Fig. 2 Transfer characteristics of IZO, IWO, and WIZO active layer based TFTs: (a) I_{DS} versus V_{GS} plot at $V_{DS} = 0.1$ V, (b) $\sqrt{I_{DS}}$ versus V_{GS} plot at $V_{DS} = 10$ V, (c) semi-log plot of I_{DS} versus V_{GS} at $V_{DS} = 10$ V, and (d) I_{DS} versus V_{GS} at $V_{DS} = 10$ V after stressing at $V_{GS} = +20$ V for different time intervals (zero - 2000 s), for deduction of mobility, threshold voltage, sub-threshold swing, and PBS shift, respectively.

(Table 1); the indium can form interstitials near oxygen vacancy in the host In_2O_3 of IWO result the film more conducting [11]. While indium zinc oxide ($M_{\text{In}} \sim 0.25$) TFT displayed good thin film transistor characteristics with field effect mobility of $19.90 \text{ cm}^2/\text{Vs}$, threshold voltage of 1.75 V and sub-threshold swing of 0.46 V/decade . The tungsten containing IZO (WIZO) TFT with molar indium cation ratio (M_{In}) of 0.44 (Table 1) displayed desirable and better thin film transistor device characteristics with field effect mobility of $22.30 \text{ cm}^2/\text{Vs}$, threshold voltage of -1.48 V and sub-threshold swing of 0.36 V/decade (Table 2). Clearly, the tungsten reduces the interface traps by controlling the surface roughness ($1.60 \text{ \AA}$) and bulk traps/localized traps in the band gap (inset of Fig.1) of the a-WIZO semiconductors and improves the mobility as well as the gate swing of the TFTs [12]. The positive gate biased stress (PBS) stability test of IZO and IWO co-sputtered IZO TFTs was studied under a V_{GS} of $+20 \text{ V}$ and a stress duration of 2000 s in dark room (Fig.2d). The V_{th} shift in the TFTs under PBS can be explained by two mechanisms: (1) the charge trapping in the gate-dielectric, and (2) the defects creation in the semiconductor; the defect creation degrades the sub-threshold swing, resulting non-parallel shift of $I_{\text{DS}}-V_{\text{GS}}$ curve [13]. Clearly, there are parallel and positive shift of $I_{\text{DS}}-V_{\text{GS}}$ curves with reducing the ON-current (I_{ON}) under the PBS (Fig.2d). This suggests that PBS stabilities of the TFTs are governed by charge trapping mechanism. Under PBS, the electrons are injected into the gate-dielectric from semiconductor, leading gate dielectric more negative. Therefore, the number of induced electrons in the semiconductor channel layer becomes lower to result smaller ON-current and positive shift in V_{th} . In addition, WIZO TFT displays much smaller PBS shift ($\Delta V_{\text{th}} \sim 1.23 \text{ V}$) than the IZO TFT ($\Delta V_{\text{th}} \sim 7.79 \text{ V}$). In IZO TFT, the bulk trap density

Table 2. The performance parameters of TFTs fabricated with various active channels.

TFT	μ_{FE} (cm^2/Vs)	SS (V/decade)	V_{th} (V)	ΔV_{th} (V)	N_{it} ($10^{12} \text{ cm}^{-3} \text{ eV}^{-1}$)
IZO (10 nm)	19.90	0.46	1.75	7.79	1.51
WIZO (10 nm)	22.30	0.36	-1.48	1.23	1.13
IWO (10 nm)	-	-	-	-	-

μ_{FE} -linear field effect mobility, SS-sub-threshold swing, V_{th} -threshold voltage, ΔV_{th} -PBS shift, N_{it} -maximum density of surface states

(i.e., charge trapping centers) is more ($\Delta E \sim 640 \text{ meV}$) which can captures more electrons from the conduction band under PBS condition. The captured electrons cause screening of applied gate bias voltage [14]. As a result, a larger positive bias is needed to turn-on the TFT. However, tungsten in IZO improves the film quality and reduces the bulk trap density ($\Delta E \sim 530 \text{ meV}$) to capture the fewer electrons. Thus, tungsten in IZO reduces the screening effect of gate bias voltage and makes the TFT more stable.

4. Conclusions

Tungsten incorporation (0.08 at.%) in IZO improves the film quality by improving the surface roughness value ($1.60 \text{ \AA}$) and reducing the tail states ($\Delta E \sim 530 \text{ meV}$) within the band gap of the semiconductor.

Thus, IZO co-sputtered IWO (WIZO) TFT prepared even at low temperature (300°C) exhibits high electrical performance with field effect mobility of $22.30 \text{ cm}^2/\text{Vs}$, subthreshold swing of 0.36 V/decade , threshold voltage of -1.48 V and positive bias stability ($\Delta V_{th} \sim 1.23 \text{ V}$), promising to apply for flexible electronics and other relevant applications.

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