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Amorphous gallium indium zinc oxide thin film transistors: Sensitive to oxygen molecules
Environment-dependent thermal instability of sol-gel derived amorphous indium-gallium-zinc-oxide thin film transistors

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The environment-dependent electrical performances as a function of temperature for sol-gel derived amorphous indium-gallium-zinc-oxide (a-IGZO) thin film transistors are investigated in this letter. In the ambient without oxygen, thermal activation dominates and enhances device performance. In oxygen-containing environments, mobility and drain current degrades and the threshold slightly increase as temperature increases. We develop a porous model for a-IGZO film relating to the drain current and mobility lowering due to film porosity and oxygen adsorption/penetration. It also relates to the threshold voltage recovery at high temperature owing to the varying form of adsorbed oxygen and the combination of oxygen and vacancies. © 2011 American Institute of Physics.

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Zinc oxide-based materials have been extensively investigated as active layers in thin film transistors (TFTs) for optoelectronic electronics such as active matrix liquid crystal displays (AMLCDs) due to the potential applications of low cost and large area deposition.1,2 Compared to conventional amorphous silicon (a-Si) TFTs, amorphous indium-gallium-zinc-oxide (a-IGZO) TFTs have similar device performance, while they have more advantages of low manufacturing cost and a process flow compatible with conventional a-Si TFTs.3,4

Having uniform and stable performance in AMLCD, stable transfer characteristics such as threshold voltage ($V_t$) and field effect mobility ($\mu_{eff}$) are essential. In real working mode, the TFT array might experience a temperature stress, generated by prolonged operation. It is important to investigate the sensitivity of temperature, which affects adsorbing modes in a-IGZO TFTs. The a-IGZO film loses oxygen easily owing to their low oxygen-vacancy formation energies, and causes a change in device characteristics with increasing temperature.5 However, there appears to be a lack of contribution to the operating temperature characteristics of a-IGZO TFTs. Takechi et al.6 ascribed the lower threshold voltage at higher temperatures to the generation of oxygen-vacancies. Hoshino et al.7 explained this observation attributed to the more populated conduction band states with temperature elevation. The similar trend is also observed in this study. The above two literatures, however, did not consider the ambient effect, which may affect the electrical characteristics of a-IGZO TFTs significantly.8 Thus, the work presented herein is to report on the temperature dependence of electrical characteristics for sol-gel derived a-IGZO TFTs in atmospheric and vacuum ambients. We also develop a model of porous film, relating to the incorporation of charged oxygen ions into the sol-gel derived a-IGZO film as temperature increases.

A schematic cross-section of coplanar-type bottom-gate a-IGZO TFTs examined here is depicted in the inset of Fig. 1. Details of the device fabrication have been reported elsewhere.9 An 80-nm-thick a-IGZO thin film was deposited as active layer by spin-coating at room temperature and then

FIG. 1. (Color online) (a) Transfer characteristics at $V_{DS}=10$ V and (b) output characteristics at $V_G-V_t=5$ V at different temperatures for a-IGZO TFTs in atmosphere. The arrow shows the drain current trend as the temperature increases. The insets of (a) demonstrated the device structure of a-IGZO TFTs.

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baked in a furnace at 450 °C for 1 hr to improve the film quality, and the molar ratio is In/Ga/Zn=1:1:2. The post-deposition annealing was conducted at 120 °C to remove the absorbent water due to the wet etching process. The channel width and length of devices were 500/50 μm. All measurements of current-voltage characteristics were performed at various temperatures (from 30 to 120 °C) in atmosphere (760 Torr) and vacuum (1 × 10^-4 Torr). According to the saturation current equation, $I_{DS}$ and $V_t$ can be calculated from the slope and the abscissa intercept from the plot of $I_{DS}^{1/2}$ versus $V_G$.

Figure 1(a) shows the transfer characteristics of a-IGZO TFTs, obtained at $V_{DS}=10$ V, at different temperatures in atmosphere. As seen in this figure, except the finding at 120 °C, the drain current ($I_{DS}$) in the entire gate voltage ($V_G$) region increases and the transfer characteristics curve shifts to more negative gate voltage with the increasing temperature, which seems to be thermally activated. The $V_t$ lowering with increasing temperature can be attributed to the free electrons generated along with oxygen-vacancies, because the thermally excited oxygen atoms leave their original sites. An alternative explanation for this finding is ascribed to the more populated conduction band states (the conduction band electron density) as the temperature increases. However, an intrigued trend of $I_{DS}$ occurred which we observed from the output characteristics, as shown in Fig. 1(b). The $I_{DS}$ decreases gradually with increasing temperature, at $V_G-V_t=5$ V. The arrow indicates the $I_{DS}$ trend as the ambient temperature increases. This unusual phenomenon may be attributed to the ambient effect of a-IGZO TFTs, especially oxygen adsorption, because with the temperature of 120 °C it is supposed that water molecules can be desorbed. To eliminate ambient effect, following measurement was performed in vacuum. Figure 2(a) shows the same trend of transfer characteristics as that in atmosphere, due to the thermally activated vacancy formation. In contrast, $I_{DS}$ apparently increases with the increasing temperature, different from the results in atmosphere. Hence, the strange trend of $I_{DS}$ in atmosphere can be ascribed to the ambient effect of a-IGZO TFTs.

Previous research indicated that the conductivity of oxide semiconductors is affected by surrounding environment, causing the conductance activation energy ($E_A$) variation. The $E_A$ can be calculated as a function of $V_t$ from the fitting of the temperature-dependent log($I_{DS}$) versus 1/T curve, where $E_A=E_C-E_F$. Figure 3(a) shows $E_A$ as a function of $V_G$ of two surrounding environments. The $E_A$ of a-IGZO TFTs extracted is 1.44 eV in atmosphere, and 0.58 eV in vacuum. The higher $E_A$ in atmosphere is due to the high barrier-height induced by charged oxygen molecules (O$_2^-$), while the low $E_A$ is ascribed to the lack of oxygen adsorption on a-IGZO film. Thus, the $V_t$ in atmosphere would be larger than in vacuum because of the higher barrier-height for electrons to overcome. The temperature dependence on $V_t$ is shown in Fig. 3(b). The results in two environments both display the $V_t$ reduction due to the temperature activated process of subthreshold drain current, and are consistent with the speculation that the $V_t$ in atmosphere is larger than in vacuum. Nevertheless, the $V_t$ exhibits slight recovery at 120 °C, which may be ascribed to oxygen effect.

With temperature increasing, $\mu_{eff}$ increases in vacuum but decreases in atmosphere, as shown in Fig. 3(c). Since mobility is a strong function of temperature, $\mu_{eff} \propto \exp(-E_A/kT)$, the increase in mobility under vacuum can be ascribed to the populated conduction band states enhancement at higher temperatures. However, the mobility decrease in atmosphere can be attributed to the repulsion of charged oxygen ions as the temperature gradually increases.

![Figure 2](image2.png)

**FIG. 2.** (Color online) (a) Transfer characteristics at $V_{DS}=10$ V and (b) output characteristics at $V_G-V_t=5$ V at different temperatures for a-IGZO TFTs in vacuum. The arrow shows the drain current trend as the temperature increases.

![Figure 3](image3.png)

**FIG. 3.** (Color online) Variations in (a) conductance activation energy, (b) threshold voltage, and (c) mobility with temperatures of a-IGZO TFTs in atmospheric and vacuum ambiances.
From SEM image of a-IGZO film [Fig. 4(a)], the resulting film with high surface roughness is rather porous, which may allow the adsorbed oxygen ions to easily penetrate a-IGZO film instead of only adsorbing on oxide surface. Takata et al. observed that in an air environment, the stable adsorbed oxygen ions on a-IGZO surface are $O_2^-$ below 100 °C [Eq. (1)] and $O^-$ between 100 and 300 °C [Eq. (2)] by capturing electrons from a-IGZO films.\(^{15-17}\) The oxygen adsorption on a-IGZO surface can be explained by the following equations:

$$O_{2(\text{ads})} + e^- \rightleftharpoons O_{2(\text{ads})}^-, \quad \text{(1)}$$

$$O_{2(\text{ads})} + 2e^- \rightleftharpoons 2O_{(\text{ads})}^- , \quad \text{(2)}$$

The free electrons transporting in a-IGZO layer will suffer from scattering by the repulsion of charged oxygen ions, causing mobility decrease with temperature elevation. The proposed model of charged oxygen ions in porous a-IGZO film is shown in Fig. 4(b). Here, we suggest that the mobility variation in atmosphere is dominated by scattering effect, while the mobility in vacuum is mainly determined by temperature effect. From the simple relation between mobility and current density, $J = ne\mu_{\text{eff}}E$, $I_{\text{DS}}$ undoubtedly decreases as observed from $I_{\text{DS}}V_{\text{DS}}$ curve. As the temperature increases above 100 °C, the adsorption form of oxygen ions changes from $O_2^-$ to $O^-$, causing the volume of oxygen ions to decrease. Because of film porosity and oxygen volume reduction, $O^-$ can penetrate the a-IGZO film more deeply and have a tendency to bond with oxygen-vacancies. This bonding behavior between oxygen ions and vacancies can be regarded as vacancy repairment. Then, owing to the structure integrity improvement, the conductivity of the a-IGZO film decreases, leading to the slight increase in $V_t$, as shown in Fig. 3(b).

In conclusion, the temperature-related oxygen adsorption in a-IGZO film has significant influences on device characteristics. As temperature increases, the enhancement of threshold voltage, drain current, and mobility in vacuum is mainly due to thermal activation, inducing oxygen-vacancies and free electrons. However, in an oxygen-containing environment, the mobility and drain current lowering obtained from output characteristics and the slight increase in threshold voltage are mainly determined by the adsorption of charged oxygen ions. As the oxygen gas adsorbs in porous a-IGZO films, scattering of charged oxygen molecules and combination of oxygen and vacancies occur with increasing temperature, owing to the film porosity and the change in oxygen adsorption form. Moreover, the $E_A$ in atmosphere is 1.44 eV and about 0.58 eV in vacuum, owing to the adsorbed charged oxygen ions.

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