

Environment-dependent thermal instability of sol-gel derived amorphous indium-gallium-zinc-oxide thin film transistors

Wan-Fang Chung, Ting-Chang Chang, Hung-Wei Li, Shih-Ching Chen, Yu-Chun Chen, Tseung-Yuen Tseng, and Ya-Hsiang Tai

Citation: *Applied Physics Letters* **98**, 152109 (2011); doi: 10.1063/1.3580614

View online: <http://dx.doi.org/10.1063/1.3580614>

View Table of Contents: <http://scitation.aip.org/content/aip/journal/apl/98/15?ver=pdfcov>

Published by the [AIP Publishing](#)

Articles you may be interested in

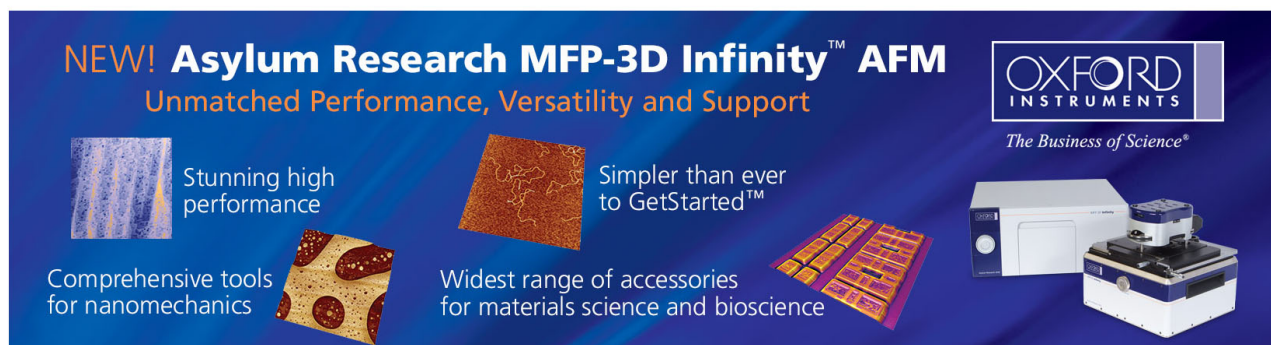
[Coplanar amorphous-indium-gallium-zinc-oxide thin film transistor with He plasma treated heavily doped layer](#)
Appl. Phys. Lett. **104**, 022115 (2014); 10.1063/1.4862320

[Effect of annealing time on bias stress and light-induced instabilities in amorphous indium-gallium-zinc-oxide thin-film transistors](#)
J. Appl. Phys. **110**, 114503 (2011); 10.1063/1.3662869

[Room-temperature-operated sensitive hybrid gas sensor based on amorphous indium gallium zinc oxide thin-film transistors](#)
Appl. Phys. Lett. **98**, 253503 (2011); 10.1063/1.3601488

[Light induced instabilities in amorphous indium-gallium-zinc-oxide thin-film transistors](#)
Appl. Phys. Lett. **97**, 173506 (2010); 10.1063/1.3503971

[Amorphous gallium indium zinc oxide thin film transistors: Sensitive to oxygen molecules](#)
Appl. Phys. Lett. **90**, 192101 (2007); 10.1063/1.2723543

The advertisement features a dark blue background with a grid of images showing various AFM scan results. The text is in white and orange. The Oxford Instruments logo is in the top right corner. The main headline is 'NEW! Asylum Research MFP-3D Infinity™ AFM' followed by 'Unmatched Performance, Versatility and Support'. Below this, there are four columns of text with corresponding images: 'Stunning high performance' with a blue and white scan image; 'Simpler than ever to GetStarted™' with a brown and white scan image; 'Comprehensive tools for nanomechanics' with a yellow and white scan image; and 'Widest range of accessories for materials science and bioscience' with a yellow and white scan image. On the right side, there is a photograph of the MFP-3D Infinity AFM system, including the main unit and a smaller probe head unit.

NEW! Asylum Research MFP-3D Infinity™ AFM
Unmatched Performance, Versatility and Support

OXFORD INSTRUMENTS
The Business of Science®

Stunning high performance

Simpler than ever to GetStarted™

Comprehensive tools for nanomechanics

Widest range of accessories for materials science and bioscience

Environment-dependent thermal instability of sol-gel derived amorphous indium-gallium-zinc-oxide thin film transistors

Wan-Fang Chung,¹ Ting-Chang Chang,^{2,3,a)} Hung-Wei Li,⁴ Shih-Ching Chen,² Yu-Chun Chen,² Tseung-Yuen Tseng,¹ and Ya-Hsiang Tai⁵

¹Department of Electronics Engineering, Institute of Electronics, National Chiao Tung University, Hsinchu 300, Taiwan

²Department of Physics, National Sun Yat-Sen University, Kaohsiung 804, Taiwan

³Center for Nanoscience and Nanotechnology, National Sun Yat-Sen University, Kaohsiung 804, Taiwan

⁴Department of Photonics, Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 300, Taiwan

⁵Department of Photonics, Display Institute, National Chiao Tung University, Hsinchu 300, Taiwan

(Received 2 February 2011; accepted 31 March 2011; published online 14 April 2011)

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 ambients 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.

[doi:10.1063/1.3580614]

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 (μ_{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 contri-

bution 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

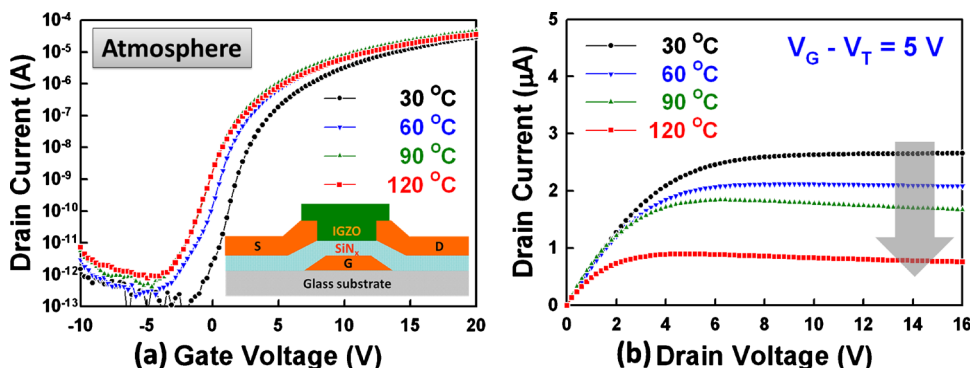


FIG. 1. (Color online) (a) Transfer characteristics at $V_{DS}=10$ V and (b) output characteristics at $V_G - V_T = 5$ V at different temperatures for *a*-IGZO TFTs in atmosphere. The arrow shows the drain current trend as the temperature increases. The insets of (a) demonstrated the device structure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

^{a)} Author to whom correspondence should be addressed. Electronic mail: tchang@mail.phys.nsysu.edu.tw.

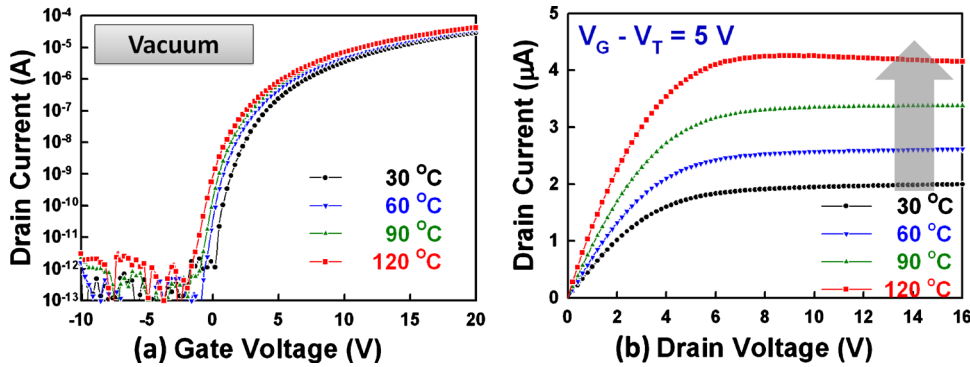


FIG. 2. (Color online) (a) Transfer characteristics at $V_{DS}=10$ V and (b) output characteristics at $V_G - V_T = 5$ V at different temperatures for *a*-IGZO TFTs in vacuum. The arrow shows the drain current trend as the temperature increases.

baked in a furnace at 450 °C for 1hr 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, μ_{eff} and V_t can be calculated from the slope and the abscissa intercept from the plot of $I_{DS}^{1/2}$ versus V_G .¹⁰

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.¹¹ 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.^{6,7} 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 ther-

mally 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.¹² The E_A can be calculated as a function of V_G from the fitting of the temperature-dependent $\log(I_{DS})$ versus $1/T$ curve, where $E_A = E_C - E_F$.^{13,14} 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, μ_{eff} increases in vacuum but decreases in atmosphere, as shown in Fig. 3(c). Since mobility is a strong function of temperature, $\mu_{\text{eff}} \propto \exp(-E_A/kT)$, the increase in mobility under vacuum can be ascribed to the populated conduction band states enhancement at higher temperatures.⁷ However, the mobility decrease in atmosphere can be attributed to the repulsion of charged oxygen ions as the temperature gradually increases.

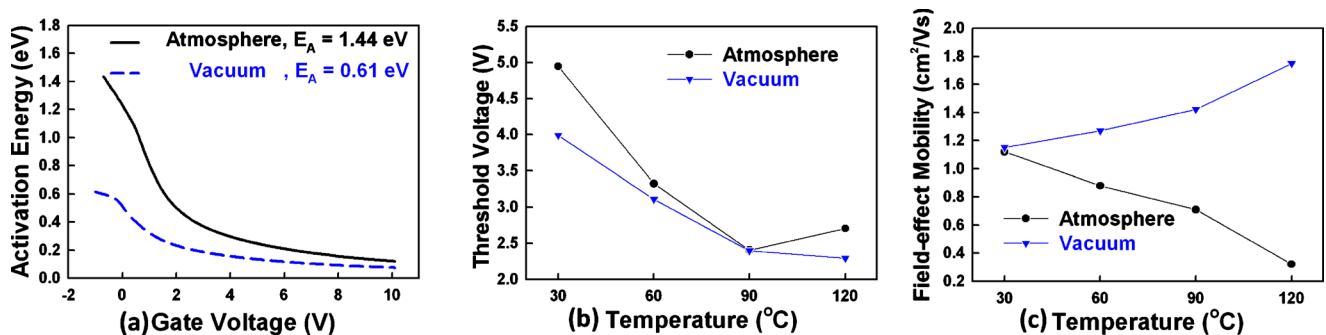


FIG. 3. (Color online) Variations in (a) conductance activation energy, (b) threshold voltage, and (c) mobility with temperatures of *a*-IGZO TFTs in atmospheric and vacuum ambiances.

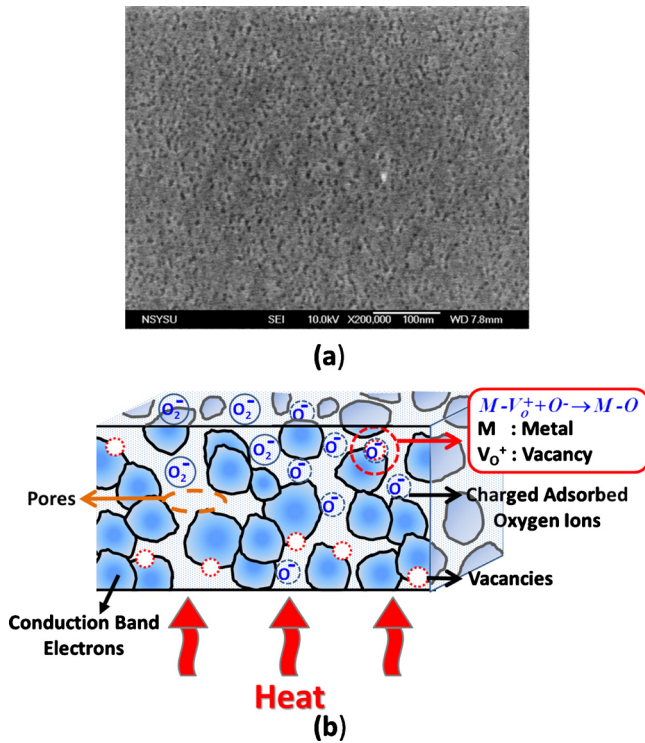


FIG. 4. (Color online) (a) SEM image of spin-coated *a*-IGZO film on wafer. The image is a top view with a scale of 100 nm and shows the film porosity. (b) Schematic penetration model of the adsorbed oxygen ions in a porous *a*-IGZO film.

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:



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, $J = ne\mu_{eff}E$, I_{DS} undoubtedly decreases as observed from I_{DS} - V_{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.

This work was performed at National Science Council Core Facilities Laboratory for Nano-Science and Nano-Technology in Kaohsiung-Pingtung area and was supported by the National Science Council of the Republic of China under Contract Nos. NSC-98-3114-M-110-001 and NSC 97-2112-M-110-009-MY3.

- ¹R. B. M. Cross, M. M. De Souza, S. C. Deane, and N. D. Young, *IEEE Trans. Electron Devices* **55**, 1109 (2008).
- ²J. Y. Kwon, K. S. Son, J. S. Jung, T. S. Kim, M. K. Ryu, K. B. Park, B. W. Yoo, J. W. Kim, Y. G. Lee, K. C. Park, S. Y. Lee, and J. M. Kim, *IEEE Electron Device Lett.* **29**, 1309 (2008).
- ³G. H. Kim, H. S. Shin, B. D. Ahn, K. H. Kim, W. J. Park, and H. J. Kim, *J. Electrochem. Soc.* **156**, H7 (2009).
- ⁴G. H. Kim, H. S. Kim, H. S. Shin, B. D. Ahn, K. H. Kim, and H. J. Kim, *Thin Solid Films* **517**, 4007 (2009).
- ⁵M. Takahashi, H. Kishida, A. Miyanaga, and S. Yamazaki, Proceedings of International Display Workshop '08, 2008, pp. 1637–1640.
- ⁶K. Takechi, M. Nakata, T. Eguchi, H. Yamaguchi, and S. Kaneko, *Jpn. J. Appl. Phys.* **48**, 011301 (2009).
- ⁷K. Hoshino and J. F. Wager, *IEEE Electron Device Lett.* **31**, 818 (2010).
- ⁸S.-Y. Sung, J. H. Choi, U. B. Han, K. C. Lee, J.-H. Lee, J.-J. Kim, W. Lim, S. J. Pearton, D. P. Norton, and Y.-W. Heo, *Appl. Phys. Lett.* **96**, 102107 (2010).
- ⁹W. F. Chung, T. C. Chang, H. W. Li, C. W. Chen, Y. C. Chen, S. C. Chen, T. Y. Tseng, and Y. H. Tai, *Electrochem. Solid-State Lett.* **14**, H114 (2011).
- ¹⁰S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed. (Wiley, New York, 1981).
- ¹¹A. Janotti and C. G. Van de Walle, *Appl. Phys. Lett.* **87**, 122102 (2005).
- ¹²Y. Muraoka, N. Takubo, and Z. Hiroi, *J. Appl. Phys.* **105**, 103702 (2009).
- ¹³H. C. Slade, M. S. Shur, S. C. Deane, and M. Hack, *Appl. Phys. Lett.* **69**, 2560 (1996).
- ¹⁴L. Pichon, A. Mercha, R. Carin, O. Bonnaud, T. Mohammed-Brahim, Y. Helen, and R. Rogel, *Appl. Phys. Lett.* **77**, 576 (2000).
- ¹⁵P. Esser and W. Göpel, *Surf. Sci.* **97**, 309 (1980).
- ¹⁶D. M. Wilson, S. Hoyt, J. Janata, K. Booksh, and L. Abando, *IEEE Sens. J.* **1**, 256 (2001).
- ¹⁷M. Takata, D. Tsubone, and H. Yanagida, *J. Am. Ceram. Soc.* **59**, 4 (1976).