Effect of exposure to ultraviolet-activated oxygen on the electrical characteristics of amorphous indium gallium zinc oxide thin film transistors

Liu, P.; Li, X. D.; Liu, Z.; Wong, J. I.; Liu, Y.; Leong, K. C.; Chen, Tupei

2013

Liu, P., Chen, T., Li, X. D., Liu, Z., Wong, J. I., Liu, Y., & Leong, K. C. (2013). Effect of exposure to ultraviolet-activated oxygen on the electrical characteristics of amorphous indium gallium zinc oxide thin film transistors. *ECS solid state letters*, 2(4), Q21-Q24.

<https://hdl.handle.net/10356/98140>

<https://doi.org/10.1149/2.005304ssl>

© 2013 The Electrochemical Society. This paper was published in *ECS Solid State Letters* and is made available as an electronic reprint (preprint) with permission of The Electrochemical Society. The paper can be found at the following official DOI: [<http://dx.doi.org/10.1149/2.005304ssl>]. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Downloaded on 26 Apr 2023 17:49:03 SGT

Effect of Exposure to Ultraviolet-Activated Oxygen on the Electrical Characteristics of Amorphous Indium Gallium Zinc Oxide Thin Film Transistors

P. Liu,^{a,z} T. P. Chen,^{a,z} X. D. Li,^a Z. Liu,^b J. I. Wong,^a Y. Liu,^c and K. C. Leong^d

^aSchool of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798

^bSchool of Materials and Energy, Guangdong University of Technology, Guangzhou 510006, China

^cState Key Laboratory of Electronic Thin Films and Integrated Devices, University of Electronic Science and Technology of China, Chengdu, Sichuan 610054, China

^dGLOBALFOUNDRIES Singapore Pte Ltd, Singapore 738406

An exposure of the back channel of an indium gallium zinc oxide (IGZO) thin film transistor (TFT) to ultraviolet (UV)-activated oxygen can effectively shift the threshold voltage (V_{th}) of the TFT. The V_{th} decreases linearly with the exposure time while the on-state current greatly increase with the exposure time. The exposure doesn't have a strong impact on other device parameters. The effect of the exposure on the V_{th} is attributed to the increase in the electron concentration of the channel layer as a result of the creation of oxygen vacancies by exposure.

© 2013 The Electrochemical Society. [DOI: 10.1149/2.005304ssl] All rights reserved.

Manuscript submitted November 9, 2012; revised manuscript received January 23, 2013. Published January 31, 2013.

Transparent oxide semiconductors (TOS) have attracted much attention for the application of flat-panel displays due to their high carrier mobility ($>1 \text{ cm}^2/\text{V s}$) and high transparency in visible range.¹⁻³ Amorphous indium gallium zinc oxide (a-IGZO) is one of the most attractive TOS that can be used in the next-generation active-matrix flat panel displays, because it has a few superior properties including relatively high mobility, good uniformity, low temperature process, high optical transparency, high threshold voltage stability, etc.^{4,5} It has been recently reported that the threshold voltage (V_{th}) of a-IGZO thin film transistors (TFTs) is affected by the process parameters such as deposition pressure, target composition, channel thickness, post annealing temperature.^{6,7} The oxygen content and the thickness of the a-IGZO channel layer are also reported to play an important role in the electrical characteristics including the V_{th} of the TFTs.^{8,9} The V_{th} is determined by the electron concentration in the channel layer of the TFT, thus it is related to the oxygen vacancies which provide the free charge carriers for electrical conduction in the oxide layer. Controlling the V_{th} is required in the TFT application; however, it is not an easy task as the oxygen vacancies can be easily generated during the fabrication processes.

In the present work, we have demonstrated that the V_{th} can be easily changed by exposing the back channel of the IGZO TFT to ultraviolet (UV)-activated oxygen. The V_{th} of the TFT is found to be highly sensitive to the exposure to UV-activated oxygen, and a linear relationship between the V_{th} shift and the exposure time is observed. However, the exposure does not have a large impact on other device parameters including the field-effect mobility and subthreshold swing.

The IGZO TFTs were fabricated on a heavily-doped n-type Si substrate with resistivity lower than $0.001 \Omega \cdot \text{cm}$, which served as the bottom gate of the TFTs. Firstly, a 30 nm Al_2O_3 layer was deposited onto the Si substrate by an atomic layer deposition (ALD) process to form the gate insulator. A 50 nm IGZO thin film was subsequently deposited on the Al_2O_3 thin film layer by radio-frequency sputtering in Ar ambient at room temperature using a IGZO target (In:Ga:Zn mole ratio = 1:1:1). The IGZO thin film was then subject to the exposure to UV-activated oxygen for different durations. Photolithography process followed by wet etching was used to pattern the active region. Finally, 200 nm thick Al source and drain electrodes were deposited by electron-beam evaporation and patterned through the standard lift-off processes to form the TFT structures. The channel length (L) and channel width (W) of the a-IGZO TFTs were 20 μm and 20 μm , respectively. The device structure of the bottom-gated TFTs device structure and the experimental setup for the UV-activated oxygen treatment are shown in Fig. 1. An UV lamp with the light wavelength

of 254 nm was used as the UV excitation source. As shown in the figure, exposure of the surface of the IGZO layer to UV-activated oxygen was carried out inside the chamber, where highly reactive oxygen was generated when the UV light interacted with the oxygen gas introduced into the chamber at room temperature.¹⁰ The resistivity and carrier concentration of the IGZO thin films with different exposure durations were measured with the four-point probe technique and the Hall-effect measurement, respectively, before the formation of the source and drain of the TFTs. Current-voltage (I-V) characteristics of the TFTs were measured with a Keithley 4200 semiconductor characterization system. All the measurements were conducted at room temperature.

Figure 2a shows the resistivity of the IGZO thin film as a function of the duration of exposure to the UV-activated oxygen. The as-deposited IGZO thin film had a relatively high resistivity of $8.0 \Omega \cdot \text{cm}$. After the exposure of 60 s, the resistivity dramatically decreased to $2.0 \Omega \cdot \text{cm}$. The resistivity further decreased to $1.0 \Omega \cdot \text{cm}$ with the 180 s exposure, and became saturated for longer exposures. On the other hand, as shown in Fig. 2b, the electron concentration of the IGZO thin film increased with the exposure time. However, the electron mobility (μ) of the a-IGZO thin film, which was calculated with $\mu = 1/qn\rho$ where q is the electron charge, n is the electron concentration and ρ is the resistivity, remained at $\sim 10 \text{ cm}^2/\text{V s}$ as shown in Fig. 2c. This indicates that the electron mobility was not significantly affected by the exposure.

X-ray photoelectron spectroscopy (XPS) measurement was performed on the IGZO films before and after the exposure of 5 min. It should be pointed out that XPS is surface-sensitive but the electrical measurements are related to the bulk properties of the IGZO thin films. In addition, the top surface of the TFT channel layer was exposed to the UV-activated oxygen, although the oxygen could diffuse into the channel region through the 50 nm IGZO layer. Nevertheless, the XPS study can provide us some useful information about the effect of the exposure on the IGZO thin films. Fig. 3a shows the XPS spectra of O 1s core level of the IGZO thin film before and after the exposure. The O 1s spectrum of IGZO film can be usually deconvoluted into three Gaussian peaks denoted as the low binding energy peak (O_L), medium binding energy peak (O_M) and high binding energy peak (O_H). O_L (530.1 eV) is from the lattice oxygen atoms in a fully-coordinated environment with the metal ions; O_M (531.1 eV) is attributed to the oxygen deficient regions of the metal oxide; and O_H (532.3 eV) is due to the adsorbed O_2 , H_2O or M-OH species on the film surface.¹¹⁻¹⁴ The deconvolutions of the XPS spectra of the IGZO thin film before and after the exposure are shown in Fig. 3b and 3c, respectively. The exposure resulted in a large increase in the O_M signal but a drastic decrease in the O_H signal. The atomic ratio of O_M / O_L increased from 0.39 before the exposure to 1.46 after the exposure,

^zE-mail: liup0013@ntu.edu.sg; echentp@ntu.edu.sg

Figure 1. Schematic of the bottom-gated TFT structure and experimental set-up for exposure to UV-activated oxygen.

indicating that the exposure generated a lot of oxygen vacancies in the IGZO layer. Although the actual mechanism for the situation is not clear yet, a plausible explanation is given in the following. UV light interacts with oxygen gas to produce oxygen radicals and ozone. The UV-activated oxygen is very reactive. It could remove the oxygen species absorbed on the surface, leading to the decrease in the O_H signal. It could also react with the IGZO layer forming deficient metal oxides. Thus increase in the O_M signal was observed after the exposure. There were more oxygen vacancies in the IGZO layer after the exposure as a result of the formation of deficient metal oxide. On the other hand, the UV light itself could generate oxygen vacancies or other defects in the IGZO layer also. Since the oxygen vacancies can act as a donor in the oxide semiconductor, the electron concentra-

Figure 2. Influence of exposure to UV-activated oxygen on the electrical properties of the IGZO thin film: (a) resistivity; (b) carrier concentration; and (c) electron mobility of the IGZO films.

Figure 3. (a) O 1s core level XPS peaks of IGZO films without and with the exposure of 5 mins to UV-activated oxygen; (b) de-convolution of the XPS peak of the IGZO film without the exposure into the three Gaussian profiles denoted as O_L , O_M and O_H , respectively; and (c) de-convolution of the XPS peak of the IGZO film with the exposure.

tion increases due to the creation of oxygen vacancies as a result of exposure to the UV-activated oxygen.

Figure 4a and 4b shows the influence of the exposure to UV-activated oxygen on the transfer characteristics and output characteristics of the TFTs, respectively. As can be observed in Fig. 4a, the exposure led to a reduction in the off-state current at large negative gate biases. The phenomenon is not fully understood yet. One plausible explanation is as follows. The off-state current at large negative gate biases is related to the interfacial defect states at the IGZO/ Al_2O_3 interface, while the on-state current is due to the free electrons in the IGZO channel layer. With the exposure, oxygen vacancies are generated in the channel layer, leading to an increase in the electron concentration in the channel layer; however, the activated oxygen could also passivate the interfacial defect states,^{15,16} causing a reduction in the off-state current. Fig. 4a also shows that an exposure led to a shift of transfer curve to the negative-gate voltage indicating the decrease in V_{th} . As shown in Fig. 4b, an exposure caused a large increase in the saturated drain current, which was due to the decrease in V_{th} .

The V_{th} values obtained from the transfer characteristics of Fig. 4a are shown in Fig. 5a. As can be observed in Fig. 5a, V_{th} decreased linearly with the exposure time. As discussed early, the post-deposition treatment could create oxygen vacancies in the IGZO layer, leading to a higher concentration of free electrons in the channel. As pointed out by E. M. Cho, et al.,¹⁷ a higher concentration of free electrons in the channel layer leads to a lower threshold voltage. This is because the IGZO TFTs have an n-type conduction channel. With more free

Figure 4. Transfer (a) and output (b) characteristics of the IGZO TFTs ($W/L = 20 \mu\text{m}/20 \mu\text{m}$) for various durations of exposure to the UV-activated oxygen. The transfer characteristics were measured at the drain voltage of 0.1 V. The inset in (a) shows the corresponding transfer characteristics in linear scale of the drain current.

electrons in the channel layer, the TFTs can be turned on at a lower gate voltage. Therefore, the decrease in V_{th} with the duration of exposure to UV-activated oxygen can be attributed to the increase of the concentration of free electrons in the IGZO channel layers. The effect of exposure to UV-activated oxygen on V_{th} provides a simple way to control the threshold voltage of IGZO TFT, and the operation mode of the TFT can be changed from the enhancement mode to the depletion mode by a sufficiently long exposure (e.g. longer than 90 s in this work).

The field-effect mobility (μ) of the TFTs has been obtained with the following formula¹⁸ at the small drain voltage (V_D) of 0.1 V,

$$\mu = \frac{Lg_m}{WC_iV_D} \quad [1]$$

where C_i and g_m are the gate capacitance per unit area and maximum transconductance, respectively. Fig. 5b shows μ as a function of exposure time. μ was $11.7 \text{ cm}^2/\text{Vs}$ before exposure, it slightly increased to $12.1 \text{ cm}^2/\text{Vs}$ after the exposure of 30 s and basically remained unchanged for further exposures. Figure 5c shows the effect of exposure on the subthreshold swing (S.S) of the TFTs which was extracted from the transfer characteristics with the formula $S.S = \delta V_G / \delta \log(I_D)$.¹⁹ The S.S slightly decreased after the exposure of 30 s but remained unchanged for further exposures. The improvement in the field-effect mobility and the S.S. by the exposure of 30 s could be explained by the passivation of the defects at the interface of $\text{Al}_2\text{O}_3/\text{IGZO}$ by the UV-activated oxygen diffusing through the IGZO layer to the interface.^{15,16} However, as the interface of the gate insulator/channel was not directly exposed to the UV-activated oxygen, such effect is not very significant. On the other hand, as shown in Fig. 5d, the on-state

Figure 5. Influence of exposure to UV-activated oxygen on the device parameters of the IGZO TFT: (a) threshold voltage; (b) field-effect mobility; (c) subthreshold swing; and (d) on-state current measured at $V_D = 3 \text{ V}$ and $V_G = 3 \text{ V}$.

current (I_{on}) greatly increased with the exposure time, which was due to the decrease of the V_{th} .

In summary, the effect of exposure to UV-activated oxygen on both the electrical properties of the IGZO thin film and the electrical characteristics of the IGZO TFTs has been investigated. The exposure can effectively shift the threshold voltage of the TFT to a lower value, and a linear relationship between the V_{th} shift and the exposure duration is observed. The decrease in the V_{th} is found to be due to the increase in the electron concentration in the IGZO channel layer. On the other hand, the on-state current significantly increases with the exposure, which is due to the decrease in the V_{th} . Other device parameters including the field-effect mobility and subthreshold swing are not significantly affected by the exposure. The study shows that exposure to UV-activated oxygen is a simple way to control the V_{th} , and the TFT can be easily changed from the enhancement mode to the depletion mode with this technique.

Acknowledgment

This work has been financially supported by the SMART Innovation Center, Singapore under project No. ING11027-ENG. Y. Liu thank NSFC under project No. 61274086.

References

1. H. Q. Chiang, J. F. Wager, R. L. Hoffman, J. Jeong, and D. A. Keszler, *Appl. Phys. Lett.*, **86**, 013503 (2005).
2. E. M. C. Fortunato, P. M. C. Barquinha, A. C. M. B. G. Pimentel, A. M. F. Gonçalves, A. J. S. Marques, R. F. P. Martins, and L. M. N. Pereira, *Appl. Phys. Lett.*, **85**, 2541 (2004).
3. Jong H. Na, M. Kitamura, and Y. Arakawa, *Appl. Phys. Lett.*, **93**, 063501 (2008).
4. T. Kamiya, K. Nomura, and H. Hosono, *Sci. Technol. Adv. Mater.*, **11**, 044305 (2010).
5. K. Nomura, H. Ohta, A. Takagi, T. Kamiya, M. Hirano, and H. Hosono, *Nature*, **432**, 488 (2004).

6. P. Barquinha, L. Pereira, G. Gonçalves, R. Martins, and E. Fortunato, *J. Electrochem. Soc.*, **156**, H161 (2009).
7. J. H. Jeong, H. W. Yang, J. S. Park, J. K. Jeong, Y. G. Mo, H. D. Kim, J. Song, and C. S. Hwang, *Electrochem. Solid-State Lett.*, **11**, H157 (2008).
8. E. Chong, Y. S. Chun, S. H. Kim, and S. Y. Lee, *J. Electr. Eng. Technol.*, **6**, 539 (2011).
9. Y. Wang, X. W. Sun, K. L. Goh, H. V. Demir, and H. Y. Yu, *IEEE Trans. Electron Devices*, **58**, 480 (2011).
10. S. Ramanathan, G. D. Wilk, D. A. Muller, C. M. Park, and P. C. McIntyre, *Appl. Phys. Lett.*, **79** 2621 (2001).
11. B. D. Ahn, H. S. Shin, G. H. Kim, J. S. Park, and H. J. Kim, *Jpn. J. Appl. Phys.*, **48**, 03B019 (2009).
12. G. H. Kim, W. H. Jeong, and H. J. Kim, *Phys. Status Solidi A*, **207**, 1677 (2010).
13. S. Jeong, Y. G. Ha, J. Moon, A. Facchetti, and T. J. Marks, *Adv. Mater.*, **22**, 1346 (2010).
14. K. K. Banger, Y. Yamashita, K. Mori, R. L. Peterson, T. Leedham, J. Rickard, and H. Sirringhaus, *Nature Mater.*, **10**, 45 (2011).
15. Y. Zhao, K. Kita, K. Kyuno, and A. Toriumi, *Jpn. J. Appl. Phys.*, **46**, 4189 (2007).
16. K. S. Yew and D. S. Ang, *IEEE Trans. Electron Devices*, **59**, 2268 (2012).
17. E. N. Cho, K. Jung Han, and Y. Ilgu, *Microelectronics Reliability*, **51**(9-11), 1792 (2011).
18. J. S. Park, J. K. Jeong, Y. G. Mo, and H. D. Kim, *Appl. Phys. Lett.*, **90**, 262106 (2007).
19. T. C. Fung, K. Abe, H. Kumomi, and J. Kanicki, *J. Display Technol.*, **5**, 452 (2009).