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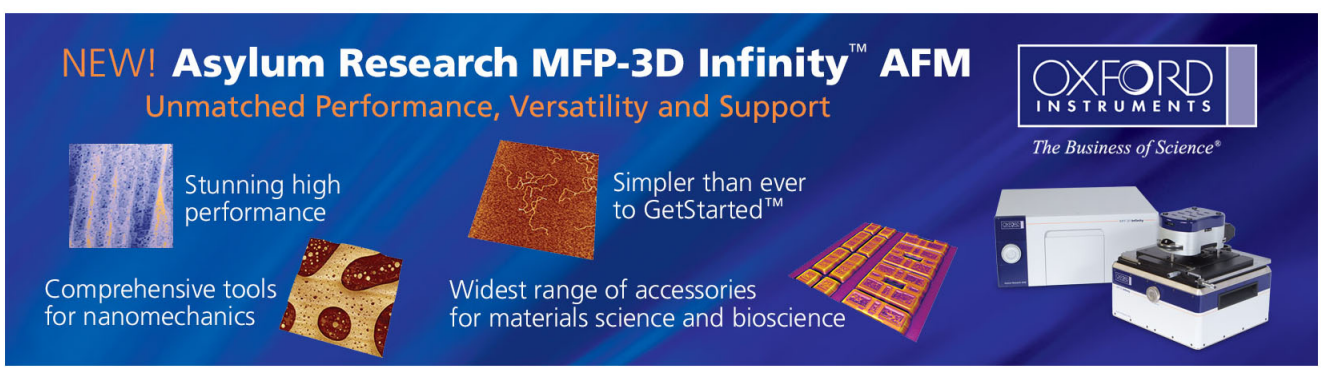

High-stability oxygen sensor based on amorphous zinc tin oxide thin film transistor

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This research presents a sol-gel derived zinc tin oxide thin film transistor (TFT) as a high-stability oxygen sensor. Due to its high sensitivity, oxygen has been traditionally regarded as having a negative influence on the electrical characteristics of zinc-based TFTs; however, TFTs can also act as an oxygen sensor. After illumination with visible light in oxygen-rich ambient, a significant increase in drain current of nearly 10^4 times occurs with fixed gate and drain voltages. It is expected that an optimized method of illumination can help to reset the electrical characteristics or distinguish the on/off state of this reliable oxygen sensor. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4731773]

During recent years, amorphous oxide semiconductors (AOSs) have shown great progress as materials crucial to thin film transistors (TFTs).[1] In particular, one of the most fruitful areas of AOSs research has focused on zinc-based semiconductors owing to potential applications involving active matrix organic light-emitting diode products or other functions in innovative future displays.[2,3] Compared to conventional polycrystalline-silicon, the zinc-based AOSs attain low cost and good uniformity over a large area deposition by sputtering or by the sol-gel method.[4] Although the electrical characteristics are superior to amorphous hydrogenated-silicon, the sensitivity of zinc-based TFTs to environment factors still remains a disadvantage when considered as a switching element.[5,6] Several studies have suggested that the varying conductivity under illumination is associated with oxygen adsorption/desorption in the backchannel of the active layer.[1,7] In this Letter, the unique oxygen sensitivity of sol-gel derived amorphous zinc tin oxide (a-ZTO) TFTs is utilized to develop a room-temperature-operated oxygen sensor. Moreover, illumination with visible light is adopted as a resetting method for the oxygen sensor, and further examined by varying the wavelength of light and operation time.

The detailed fabrication procedure of passivation-free a-ZTO TFTs with a bottom-gate bottom-contact configuration, as shown in the inset of Fig. 1, has been reported previously.[8,10] After forming a 300-nm-thick molybdenum tungsten gate and silicon nitride dielectric, source and drain electrodes were deposited by sputtered indium tin oxide. Precursor solution for fabricating spin-coated Zn-Sn-O thin films was synthesized by dissolving zinc acetate dihydrate [$Zn(OAc)_2$ $2H_2O$] and tin chloride dihydrate ($SnCl_2$ $2H_2O$) in monoethanolamine and 2-methoxyethanol at 60 °C for 3 h, respectively.[8] Next, the active channel of the a-ZTO film was deposited by spin-coating with a thickness of 80 nm at room temperature and at atmospheric pressure. The channel layer was patterned by standard photolithography and wet etching. Finally, the device was subjected to thermal annealing at 350 °C for 1 h under ambient oxygen in a furnace. The channel width and length are 50 and 8 μm, respectively. All current-voltage characteristics were measured at room temperature and in a vacuum chamber with gas-flow system and probe station using an Agilent B1500 precision semiconductor parameter analyzer. The threshold voltage (V_T) is determined by using the constant current method as the gate-to-source voltage (V_G), which induces a drain current (I_D) of 1 nA. The light illumination of 5000 lux in intensity in this work was obtained by a halogen lamp whose spectrum is shown in the inset of Fig. 2(b).

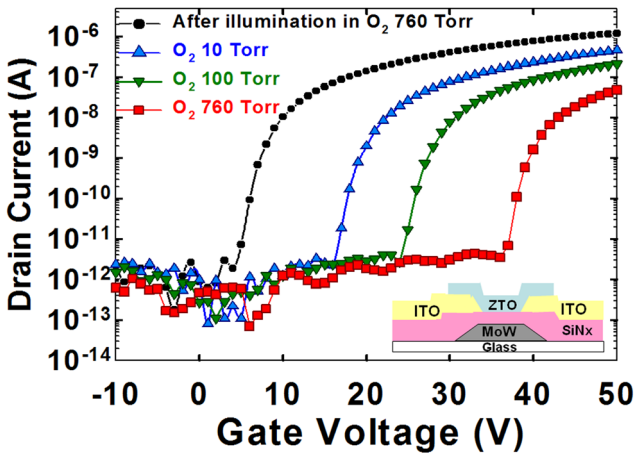

FIG. 1. Transfer I_D-V_G characteristics of a-ZTO TFTs in different oxygen partial pressures (10 torr, 100 torr, and 760 torr) and after illumination of visible light with an intensity of 5000 lux in oxygen ambient of 760 torr, respectively. The inset shows the schematic cross-sectional view of a fabricated bottom-gate a-ZTO TFT.

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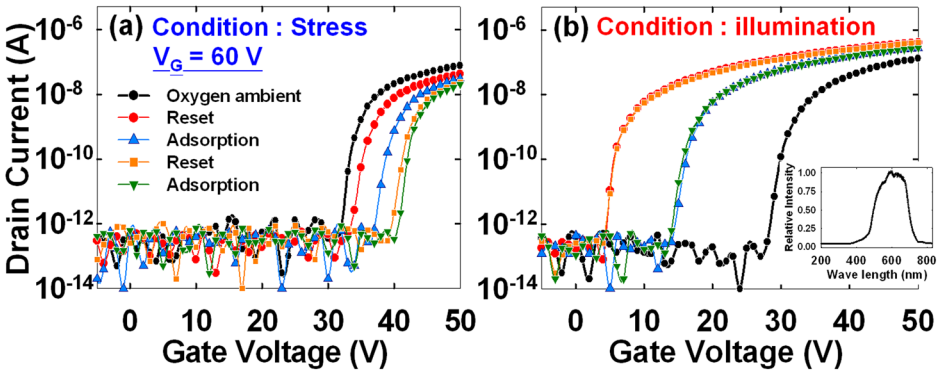

FIG. 2. (a) Transfer I_D-V_G characteristics of a-ZTO TFTs after experimental repetition of a-60-V-gate-bais for 120 s and subsequent relaxation for 120 s in oxygen ambient. (b) I_D-V_G characteristics of a-ZTO TFTs after 120 s illumination time and subsequent relaxation for 120 s in oxygen ambient.

Figure 1 shows the I_D-V_G electrical characteristics of a-ZTO TFTs at drain-to-source voltage (V_D) of 1 V, linear region, in oxygen ambient pressures of 10 torr, 100 torr, and 760 torr and after illumination of visible light in oxygen ambient of 760 torr, respectively. Clearly, the V_T variation of a-ZTO TFTs seems to be closely correlated with the amount of surrounding oxygen molecules. As the environmental oxygen increases, it exhibits a V_T shift about 20 V with rare variations in subthreshold slope. In general, literatures have described the surrounding oxygen molecules as capturing electrons from the conduction band, then causing the adsorption of oxygen ions (O^-, O^{2-}) on the active layer, resulting in a depletion layer in the backchannel and an increase in the V_T of ZTO TFTs.[6,7,9] Interestingly, after illumination with visible light for 120 s, the V_T in oxygen ambient shows drastic negative shifts. This phenomenon suggests that the photogeneration of holes discharges the negatively charged adsorbed oxygen ions. Meanwhile, electrons are released into active layer as a form of $\mathbf{O_2}^-_{\mathbf{(ads)}} + \mathbf{h}^+ \rightarrow \mathbf{O_2}_{\mathbf{(solid)}} + \mathbf{e}^-$. This result reveals the important role of oxygen, which can affect the V_T and the electrical characteristics in passivation-free devices.

The purpose of this work is to logically utilize this oxygen adsorption/desorption process to develop an oxygen sensor. Therefore, a large positive voltage is applied on the gate trying to repel holes from the front-channel to backchannel, which can therefore be expected to discharge the chemical adsorbed oxygen ions on the active layer. Figure 2(a) shows the I_D-V_G characteristics after applying 60 V on the gate for 120 s with grounded drain and source in oxygen ambient, and subsequent relaxation of 120 s with all terminals grounded in the same oxygen ambient. After applying bias or a relaxation operation, the electrical characteristics demonstrate a persistent positive shift, which means that more chemical adsorption of oxygen occurs due to gate bias operation.[10] Clearly, another efficient resetting method is required. Since the existing high-density electron traps above the valence band maximum with a large energy range, holes cannot drift to the backchannel of a-ZTO and desorb the adsorbed oxygen, unless under illumination.[4] Accordingly, a reset method is undertaken by illumination of visible light. The I_D-V_G characteristics of a-ZTO TFTs after 120 s of illumination and relaxation for 120 s both in oxygen-rich ambient are shown in Fig. 2(b), respectively. The transfer curve exhibits an obvious negative shift due to the oxygen desorption by photogeneration holes, a shift phenomenon that still occurs after experimental repetition. This suggests that the reset and adsorbed operation of an oxygen sensor can be reproduced by visible light illumination.

To further verify the characteristics of an oxygen sensor, time evolution of I_D before and after illumination for 120 s in oxygen ambient is extracted with fixed gate voltage of 8 V after repeating the oxygen adsorption/desorption cycle are shown in Fig. 3. Thus, we can differentiate the I_D between high- or low-current state, defined as the on- and off-state of the oxygen sensor, respectively. The ratio of I_D between on-state (desorption of oxygen) and off-state (adsorption of oxygen) is as high as more than 10^4 times, which is quite important in identification of the sensor state, resulting in a reduction of erroneous judgment. Moreover, the on/off states were stable and well reproduced throughout the repeated cycling. It should be noted that the fluctuation of I_D in the off-state during repeating the oxygen adsorption/desorption cycle can be attributed to the noise level of electrical measurement. However, after illumination in oxygen ambient, the oxygen can be expected to chemisorb back on the backchannel rapidly because of quick decrease in I_D after light turning off for 120 s. This result indicates that the operating condition of sensor can have more examination.

The different operating condition of oxygen sensor are examined in more detail in Fig. 4, which depicts the extracted I_D ratio of the on/off states while reducing the illumination and relaxation time from 300 s to 120 or 60 s with varying wavelength of light in the same photon flux. The monochromatic light, red (660 nm), green (550 nm), or blue

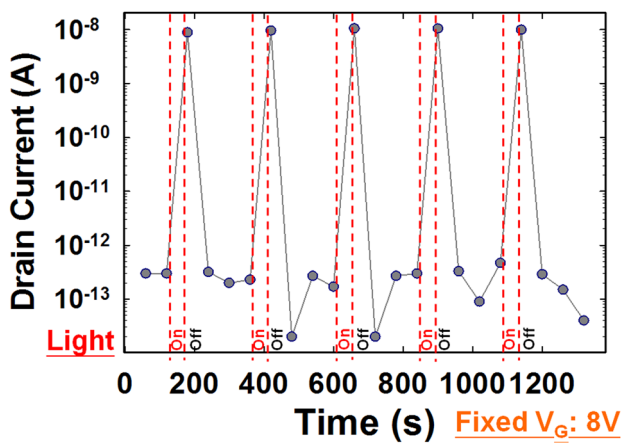

FIG. 3. Time dependence of drain current which is extracted with fixed gate voltage of 8 V and drain voltage at 1 V for repeating the oxygen adsorption/desorption cycle.

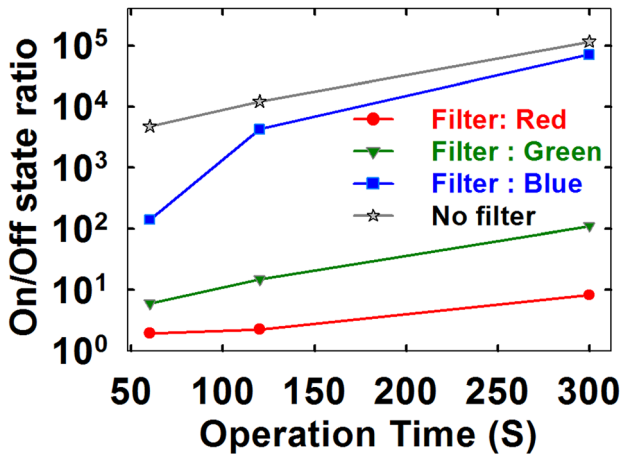

FIG. 4. Variation of extracted I_D ratio of on/off state as a function of reset and adsorption time with different wavelengths ($\lambda = 660$, 550, and 490 nm) of visible light.

(490 nm), comes from the visible light passing through optical fiber and transfers through fiber cable and probe station microscope to focus the illumination on the a-ZTO TFT channel, respectively. These results demonstrate that the monochromatic blue light is still reliable to reset the oxygen sensor to on-state. A comparison of the I_D ratio of the on/off states after different monochromatic illuminations for the same time indicates that the desorption rate of chemisorbed oxygen is a function of illuminated wavelength for the reset operation.[11,12] Since the binding energy between adsorbed oxygen species (O^-, O_2^-) and Zn-based oxide surface is more than 2 eV, the illumination of green and blue lights are expected to enhance the formation of photogeneration holes.[13]

In summary, the sol-gel derived a-ZTO TFT as an oxygen sensor with efficient operation is discussed herein. High-stable on/off state ratio about more than four orders of difference in I_D at room temperature can be reproduced and be controlled by illumination with visible light for 120 s. Consequently, the sol-gel derived a-ZTO TFTs have the advantage of acceptable electrical characteristics with low fabrication cost as a switching device and of sensitivity to surrounding oxygen molecules for use as an oxygen sensor, which can be expected to be employed in all multifunctional AOSs-based devices, known as "system-on-glass."

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[1]T. Kamiya, K. Nomura, and H. Hosono, Sci. Technol. Adv. Mater. **11**, 044305 (2010).
[2]K. M. Kim, C. W. Kim, J.-S. Heo, H. Na, and J. E. Lee, Appl. Phys. Lett. **99**, 242109 (2011).
[3]T.-C. Chang, F.-Y. Jian, S.-C. Chen, and Y.-T. Tsai, Mater. Today **14**(12), P608 (2011).
[4]T. Kamiya, K. Nomura, and H. Hosono, J. Display Technol. **5**(7), 273 (2009).
[5]W.-F. Chung, T.-C. Chang, H.-W. Li, and C.-W. Chen, Electrochem. Solid-State Lett. **14**, H114 (2010).
[6]W.-F. Chung, T.-C. Chang, H.-W. Li, S.-C. Chen, and Y.-C. Chen, Appl. Phys. Lett. **98**, 152109 (2011).
[7]Y. Takahashi, M. Kanamori, A. Kondoh, and H. Minoura, Jpn. J. Appl. Phys. **33**, 6611 (1994).
[8]S.-C. Chiang, C.-C. Yu, M.-C. Wang, and T.-C. Chang, *Taiwan Display Conference* (2008), p. B106.
[9]J. Bao, I. Shalish, Z. Su, R. Gurwitz, F. Capasso, X. Wang, and Z. Ren, Nanoscale Res. Lett. **6**, 404 (2011).
[10]Y.-C. Chen, T.-C. Chang, H.-W. Li, S.-C. Chen, J. Lu, and W.-F. Chung, Appl. Phys. Lett. **96**, 262104 (2010).
[11]P. Görrn, M. Lehnhardt, T. Riedl, and W. Kowalsky, Appl. Phys. Lett. **91**, 193504 (2007).
[12]T.-C. Chen, T.-C. Chang, T.-Y. Hsieh, S.-C. Chen, C.-S. Lin, and M.-C. Hung, Appl. Phys. Lett. **97**, 192103 (2010).
[13]J. Lagowski, E. S. Sproles, and H. C. Gatos, J. Appl. Phys. **48**, 3566 (1977).