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Oxide Thin-Film Transistors With IMO and IGZO Stacked Active Layers for UV Detection

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ABSTRACT Thin film transistors (TFTs) with amorphous InMgO (a-IMO) and InGaZnO (a-IGZO) stacked active layers are proposed to implement high-performance ultraviolet (UV) detectors. In this structure, the IGZO layer serves as the conductive layer and the IMO layer acts as the light absorption layer. The fabricated a-IGZO/a-IMO TFT shows comparable electrical characteristics to those of the conventional a-IGZO TFT as well as high UV photocurrent gain with good visible-blindness. In addition, the a-IGZO/a-IMO TFT-based sensor operates with stable and successive light detection. Thus, the a-IGZO/a-IMO TFT has been demonstrated to be able to act as both sensing and switching devices in the pixels of UV image sensors.

INDEX TERMS Thin film transistors (TFTs), ultraviolet (UV) detection, amorphous IGZO TFTs, amorphous InMgO TFTs.

I. INTRODUCTION

Amorphous oxide semiconductor thin film transistors (TFTs) have been extensively investigated in recent years as the most promising devices for applications in next generation large-area electronics [1]–[4]. Because of their wide bandgap (E_g), these TFTs have also been implemented as ultraviolet (UV) detectors [5]–[8]. The amorphous oxide-based photo-TFTs have shown a number of advantages, such as low dark current, high responsivity and a simple fabrication process, compared to conventional photodiodes [9].

The most investigated metal oxide film is the amorphous InGaZnO (a-IGZO), which is an excellent channel material for switch TFTs in active matrix displays [10]. However, the a-IGZO TFT has a high photosensitivity to visible light, making it unfavorable for UV detection with visible-blindness [11]. Mg-doped ZnO (ZMO) and In_2O_3 (IMO)-based oxide TFTs have been reported to be two promising candidates for visible-blindness UV detection [7], [12], [13]. However, these TFTs with the Mg incorporated active layers, usually exhibit poor electrical performance due to the significantly degraded mobility, precluding them from serving the switch purpose. In the UV image sensing pixel circuit, both high performance switch and sensing devices need to be fabricated in a single TFT technology [14]. Therefore, it is worthwhile to develop a TFT technology that enables both high-performance switch and sensing devices built with the same active layer material. In this work, a new oxide TFT technology with a-IGZO and a-IMO stacked active layers is proposed and demonstrated. The device fabrication process is described in detail. The electrical and optoelectronic properties of the fabricated TFTs are analyzed and discussed. The dynamic photo-response of the a-IGZO/a-IMO TFT is also investigated.

II. TFT DESIGN

The proposed a-IGZO/a-IMO stacked TFTs were fabricated in the most commonly used bottom-gate staggered structure. Fig. 1(a) shows the schematic cross-sectional views of the active layer stacked TFT. Considering that the on-current of TFTs almost distributes within the channel region of about 10-nm thickness, the thickness of the a-IGZO layer was chosen to be 10-nm. It is believed that further increasing the thickness of the a-IGZO layer does not increase the on-current evidently, but increases the responsivity to

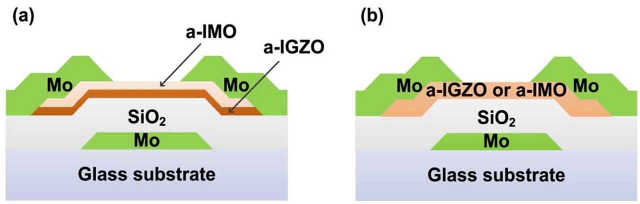

FIGURE 1. Schematic cross-sections of (a) a-IGZO/a-IMO TFT and (b) a-IMO or a-IGZO TFT.

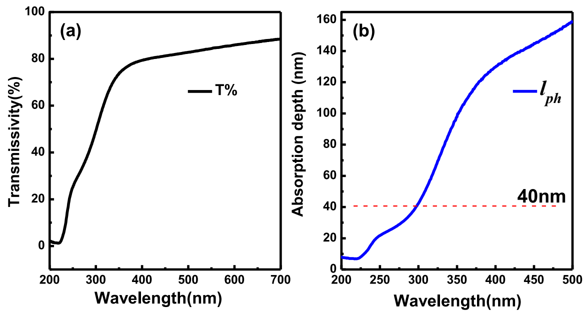

FIGURE 2. (a) The transmittance spectra of a 30-nm-thick a-IMO film. (b) Absorption depth (l_{ph}) versus wavelength, which is extracted from Fig. 2(a).

visible light. On the other hand, according to the experimental results, most of the UV light is absorbed within 40-nm of a-IMO layer. Fig. 2(a) shows the measured transmittance spectra of the a-IMO film with 30-nm thickness in the wavelength range of 200-700 nm. Absorption depth (l_{ph}) in the a-IMO film versus wavelength is shown in Fig. 2(b). l_{ph} is determined as $1/\alpha$, where α is the optical absorption coefficient. The transmissivity (T) and α is related by the following equation [15]:

$$T = \exp(-\alpha d), \quad (1)$$

where d is the thickness of the a-IMO film. As shown, the l_{ph} value at the wavelength (λ) of 300 nm is around 40 nm. This means that about 63% of photons of the incident light with 300 nm wavelength are absorbed with the 40-nm-thick a-IMO film. Although further increasing the thickness of the a-IMO could enhance the absorption, it increases the source/drain contact resistance since the a-IMO is high resistive. Therefore, the thickness of the a-IMO layer in this work was chosen to be 40-nm.

III. EXPERIMENTAL DETAILS

The proposed a-IGZO/a-IMO stacked TFTs were fabricated. For comparison, TFTs with a single a-IMO or a-IGZO active layer in the same structure were fabricated as well. Fig. 1(b) shows the schematic cross-sectional views of the single active layer TFT. The fabrication process was as follows: a 150-nm-thick Mo layer was deposited onto glass substrates by direct current (DC) sputtering at room temperature (RT) and then patterned by lift-off technique to form the gate electrode. Afterwards, a 200-nm-thick SiO_2 gate insulator was deposited by plasma-enhanced chemical vapor deposition (PECVD) at 300 °C. Subsequently, a 50-nm-thick active layer was deposited by radio frequency (RF) sputtering at RT. The active layer is either a single-layered 50 nm-thick IGZO or a-IMO, as shown in Fig. 1(a), or a stacked active layer with 10-nm-thick a-IGZO and 40-nm-thick a-IMO, as illustrated in Fig. 1(b). The composition (according to atomic ratio) of the IGZO target is Ga: In: Zn = 1: 1: 1, whereas that of the IMO target is In: Mg = 11: 9. All active layers were patterned by wet-etching in a diluted HCl solution. Next, a 150-nm-thick Mo layer was deposited by DC sputtering at RT and patterned by lift-off technique to form the source and drain electrodes. Finally, all devices were annealed in N_2 atmosphere at 250 °C for one hr. The electrical properties and optoelectronic properties of the fabricated TFTs were measured at RT using a semiconductor parameter analyzer (B1500, Agilent Technologies). Light sources were provided by a 750-W Xenon arc lamp and a 300-mm focal length monochromator that covers a wavelength range of 200-1500 nm. The incident optical power was measured by a power meter (LE-LPM-10AP). The temperature and relative humidity in the chamber were well controlled at RT and 50%, respectively, during the measurement.

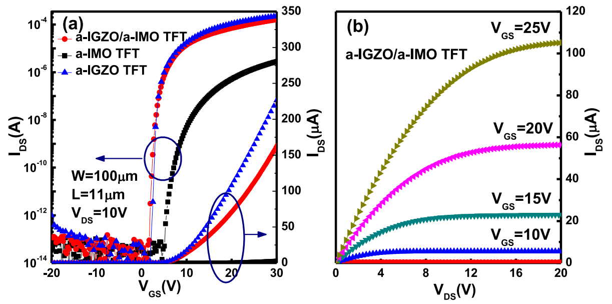

FIGURE 3. Current-voltage characteristics of the fabricated TFTs with (a) transfer ones for a-IMO, a-IGZO and a-IGZO/a-IMO TFTs and (b) output ones for the a-IGZO/a-IMO TFT in the dark only.

IV. RESULTS AND DISCUSSION

Fig. 3 shows the current-voltage characteristics of the fabricated TFTs with (a) transfer ones for the a-IMO, a-IGZO and a-IGZO/a-IMO TFTs and (b) output ones for the a-IGZO/a-IMO TFT in the dark only. The threshold voltage (V_{TH}) and saturation mobility (μ_{sat}) were extracted from the linear extrapolation of $I_{DS}^{1/2}$ versus V_{GS}. The sub-threshold swing (SS) was extracted from the linear portion of log (I_{DS}) versus V_{GS} plot. The major electrical parameters of three types of TFTs are summarized in TABLE 1. The a-IGZO/a-IMO TFT is shown to be comparable to the a-IGZO TFT in electrical performance except for its slightly lower on-current. The source/drain resistance (R_{SD}) of the TFTs was evaluated by using the transfer-length method (TLM) [16]. The width-normalized R_{SD} (R_{SD}*W) values were calculated to be 110 Ω·cm for the a-IGZO TFT and 583 Ω·cm for the a-IGZO/a-IMO TFT, signifying an inferior ohmic contact between a-IMO and Mo than between IGZO and Mo. The

TABLE 1. The major electrical parameters of fabricated TFTs.

	V_{TH} (V)	μ_{sat} ($cm^2V^{-1}s^{-1}$)	SS (V/decade)
a-IMO TFT	11.0	0.2	0.70
a-IGZO/a-IMO TFT	3.3	6.8	0.24
a-IGZO TFT	3.8	8.0	0.20

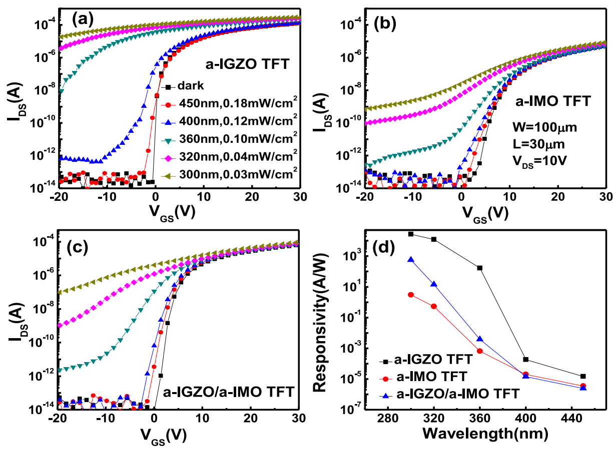

FIGURE 4. Transfer characteristic variations of (a) a-IGZO TFT (b) a-IMO TFT and (c) a-IGZO/a-IMO TFT in the dark and under various illuminations. (d) The responsivity of the three types of TFTs as a function of incident light wavelength.

larger R_{SD} is believed to lead to the lower on-current of the a-IGZO/a-IMO TFT than that of a-IGZO TFT.

However, the a-IMO TFT exhibits a very low on-current although it has been improved a lot in electrical performance compared to the earlier device [13]. The significantly lower on-current resulted from the severely degraded carrier mobility which decreased significantly with increasing Mg content in a-IMO, as has been reported earlier [13]. The a-IGZO/a-IMO TFT is thus confirmed to be good enough in the electrical performances for serving switch purpose, and the a-IMO TFT is too poor to be practical.

Fig. 4 shows the evolution of transfer characteristics of the three TFTs under various illuminations for (a) a-IGZO, (b) a-IMO, and (c) a-IGZO/a-IMO TFTs, and (d) the responsivity (R) as a function of illumination with λ ranging from 450 nm to 300 nm. R is determined as the ratio of I_{PH} to the corresponding light power at V_{GS}= -15 V and V_{DS}= 10 V, where I_{PH} is the TFT drain current difference between illumination and dark conditions. All three TFTs exhibit remarkable photo-responses in the off-state region under UV light. The a-IGZO TFT is shown to yield the highest responsivity in the measured wavelength region among the three TFTs, which may be attributed to its higher mobility and additional light excitation of the oxygen vacancies (V_O) in addition to the intrinsic band-to-band transitions. The a-IGZO is believed to exhibit the highest V_O concentration. However, the a-IGZO TFT also exhibits a high responsivity to visible light, which is not likely to be acceptable for practical applications. In contrast, the a-IGZO/a-IMO TFT shows both a relatively high responsivity to UV light and low responsivity to visible light. The UV light responsivity of the a-IGZO/a-IMO TFT is much higher than that of the a-IMO TFT, which could be ascribed to the hetero-junction structure formed between the a-IGZO and a-IMO layers, enhancing the separation of electron-hole pairs and thus promotes the responsivity [17]. Thus, the a-IGZO/a-IMO TFT has been demonstrated to exhibit a high UV light responsivity with greatly enhanced visible light blindness, making it an ideal candidate as a UV detector. It is also possible to further increase the responsivity of the TFTs to deep UV light and simultaneously decrease the responsivity to near UV light by further minimizing the oxygen vacancy density in the a-IMO and a-IGZO films or/and increasing Mg ratio of a-IMO film.

In addition to the ideal visible-blindness and high UV light responsivity, detection stability under multiple measurements is also an important requirement for a UV detector. Fig. 5 shows the dynamic response of the a-IGZO/a-IMO TFT under different gate bias and multiple light cycles. The sample was under illumination with λ = 360 nm at a power density of 0.03 mW/cm^2. The TFT was negatively biased to increase the signal-to-noise ratio. The gate bias voltages was -30 V in Fig. 5(a) and -10 V in Fig. 5(b). V_{DS} was 10 V in both cases. The period of the pulsed light was 10 s with the on-time and off-time being 3 s and 7 s, respectively. A 0.1-ms positive pulse at 10 V was applied during the recovery process. when the light was turned on, the current (I_{DS}) increased rapidly by more than four orders of magnitude at a gate bias of -30 V and two orders of magnitude at a gate bias of -10 V. After the light was turned off, the current could not immediately return to its initial value in the dark state, which is attributed to the ionized V_O states (V_O^{2+}) [18]. An energy barrier is created as a result of the outward relaxation of bonds surrounding the V_O states, which impedes the neutralization of V_O^{2+} states. In addition, the negative V_{GS} enables an effective separation of electrons and holes [19]. For the aforementioned reasons, the photocurrent persisted long after the light was turned off. By applying a positive pulse at V_{GS}, a fast recovery in the current was achieved. The current nearly recovered immediately when the gate bias voltage was -30 V, as shown in Fig. 5(a), whereas it could not fully recover when the gate bias voltage was -10 V as shown in Fig. 5(b). The positive gate pulse bias is inferred to raise the Fermi level, thereby accelerating the neutralization of V_O^{2+} states at the front channel [18], [20]. However, the oxygen vacancies in the bulk remain ionized. Therefore, the active layer still maintained a high level of carrier concentration and a high negative gate bias was needed to deplete the channel. For several light cycles and positive V_{GS} pulses, the I_{ON} and I_{OFF} was constant in the case of gate bias = - 30 V, but continued to gradually ascend in the case of gate bias = - 10 V, where I_{ON} is the current with the light on and I_{OFF} is the current with the light off. In the case of the gate bias = -10 V as shown in Fig. 5(b), the current could not return to its initial value after the light was turned off, even when a positive V_{GS} pulse was applied. The

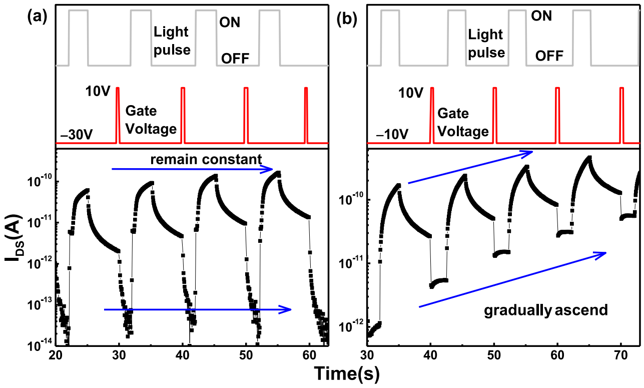

FIGURE 5. Dynamic responses of the a-IGZO/a-IMO TFT with a positive gate pulse at a gate bias of (a) −30 V and (b) −10 V. The sample was under illumination with λ = 360 nm at a power density of 0.03 mW/cm^2.

superposition of the current in the following cycles led to the gradual increase of I_{ON} and I_{OFF}. These results suggest that a high negative gate bias together with a positive V_{GS} pulse for the metal oxide photo-TFT can yield not only a high I_{ON}/I_{OFF} ratio but also a steady and successive detection.

V. CONCLUSION

The electrical and photo-electronic properties of TFTs with a-IGZO/a-IMO stacked active layers have been investigated. The electrical performance of the double layer stacked TFT was shown to be comparable to that of the a-IGZO TFT and much higher than that of the a-IMO TFT, making it an ideal switch device. What is more, the a-IGZO/a-IMO TFT exhibited much better visible-blindness than the a-IGZO TFT and a much higher photocurrent gain than the a-IMO TFT. In addition, studies of the detection stability of the a-IGZO/a-IMO TFT showed that a high negative gate bias together with a positive V_{GS} pulse is preferred to obtain successive and stable detection. The proposed a-IGZO/a-IMO TFT was thus demonstrated to be able to fulfill both functions of pixel address switching and UV sensing devices. Therefore, high performance and low cost UV image sensors are believed to be possible in the proposed oxide TFT technology.

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