Indium Gallium Oxide Thin Film Transistor for Two-Stage UV Sensor Application

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In this work, indium gallium oxide (IGO) thin film transistor (TFT) was fabricated by radio-frequency (RF) sputtering. The transmittance of the TFT shows larger than 80% across the visible light region. As a wide bandgap and high transparency semiconducting material, IGO is a potential candidate for UV-detection applications. Measured in the dark, the IGO TFT exhibits a threshold voltage of 0.9 V, mobility of 2.66 cm²/Vs, on-off ratio of 1.21 × 10⁸, subthreshold swing of 0.41 V/dec. The TFT was then employed to detect UV light and the sensing properties are investigated. The IGO phototransistor has a high responsivity of 5.012 A/W and a rejection ratio of 1.65 × 10⁷. The above results reveal that IGO phototransistor is a brilliant multi-functional device, which can serve as either a switch component or a UV sensor.

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In recent years, oxide semiconductor thin film transistors (TFTs) have been extensively studied due to their fascinating advantages, such as high carrier mobility, excellent uniformity, high transparency in the visible light range, and low processing temperature.1-7 Plenty of metal oxide semiconductors have been developed for TFT applications, including ZnO, ZnSnO, InO₃, InGaZnO, and HfInZnO.8-12 Among all, InO₃ and ZnO are well-known transparent conducting oxide materials with intrinsic oxygen deficiency that endows the material with a high mobility.13 Thus, doping of InO₃ or ZnO is a feasible method to improve TFT performance by modifying the density of oxygen vacancies.

As a wide bandgap material, Ga₂O₃-based oxide TFTs have an innate advantage for UV detection. Several previous studies have investigated the optical-electrical properties of Ga₂O₃ TFTs doped with In₂O₃ and ZnO (namely IGZO TFTs).14-16 However, Ga₂O₃-based phototransistor doped with single material, either In₂O₃ or ZnO, is not widely researched and rare in academia.

In this work, opto-electrical properties of the IGO TFTs are thoroughly discussed. To ameliorate the performance of the Ga₂O₃-based TFT, doping In₂O₃ is implemented. J. H. Park et al. and Y. G. Kim et al. have fabricated IGO TFTs by solution process.17,18 IGO TFTs fabricated by ALD is also reported by J. Z. Sheng et al. Both solution process and ALD methods need high temperature when deposition. In this work, we fabricated IGO thin film by RF sputter, which is capable under room temperature. In addition, according to the previous reports,20-23 reduction of trap density and enhancement of TFT performance could be attained by applying high-k material as gate insulator, such as Al₂O₃ (k~9), Y₂O₃ (k~14), HfO₂ (k~16), ZrO₂ (k~16), and Ta₂O₅ (k~20). By doing so, several benefits including low gate leakage current, low operation voltage, and small equivalent oxide thickness (EOT) are also achieved. Furthermore, J. J. et al. have shown that oxide-based TFTs with active layer thickness of less than 50 nm possess better electrical properties.24 With the above considerations, IGO TFTs with active layer thicknesses of 20 nm and Al₂O₃ insulating layer are fabricated. In order to assess their electrical performance and sensing ability, a few measurements were conducted in the dark and under illumination.

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Experimental

The structure of the synthesized staggered bottom-gate IGO TFTs is shown in Figure 1. The IGO TFTs were fabricated on 2 cm×2 cm quartz substrates. The substrates were cleaned with an ultrasonicator by acetone, isopropyl alcohol, and deionized water each for 5 minutes, and followed by drying under a stream of nitrogen. A 70-nm-thick Al gate electrode was first thermally evaporated on the substrate and capped with 200-nm-thick Al₂O₃ layer formed by atomic layer deposition (ALD) at 250°C. The channel of 20 nm was deposited by sputtering an IGO target (In₂O₃:Ga₂O₃ = 40:60 in mole ratio). Finally, 70-nm-thick Al source and drain electrodes were deposited in the same way as the gate electrodes. The channel width and length are 2000 μm and 100 μm, respectively. During the above processes, there is no any lithography technique included. In addition, we defined the patterns using several different metal mask.

X-ray photoelectron spectroscopy (XPS: PHI 5000 VersaProbe, ULVAC, Japan) was used to characterize the indium, gallium and oxygen species. The transparency of the 100-nm-thick IGO thin film was verified by UV-Vis-NIR spectrophotometer. The transfer characteristics were measured at room temperature by Agilent B1500A

Figure 1. Schematic of IGO thin film transistor and its cross-sectional view.
Results and Discussion

Figure 2 illustrates the optical transmittance of the IGO thin film. It is observed the film is highly transparent across the visible light region (450 nm - 800 nm). To further explore the optical properties of the material, the inset of Figure 2 depicts the relation between \((\alpha h\nu)^2\) and photon energy \(h\nu\), by applying the Tauc’s equation, which is expressed as \((\alpha h\nu)^2 = A(h\nu - E_g)\), where \(\alpha\) is the absorption coefficient corresponding to the frequency \(\nu\), \(h\) is the Planck’s constant, \(A\) is a constant, and \(E_g\) is the bandgap energy. The bandgap of IGO, estimated by extrapolating the linear part of the curve to intersect with \(y = 0\), is approximately 3.56 eV, which is desirable for transparent display applications or UV-related devices. Besides, as shown in the figure, there is the other tangent intersecting with \(y = 0\) at 2.75 eV, which is attribute to the bcc-In\(_2\)O\(_3\) in the film. The chemical element information of the IGO thin film was analyzed by XPS as shown in Figure 3. As a result, we can observe a two-stage reduction starting from 451 nm and 348 nm in Figure 2.

Figure 4 shows the current-voltage measurement result of the IGO TFT. The gate voltage was increased from 0 V to 10 V by a step of 2 V, and the drain voltage was swept from 0 V to 10 V. The TFT exhibited typical n-type behavior. The transfer characteristics of the TFT at a drain bias of 8 V are shown in Figure 5. Some important electrical characteristics of the TFT to evaluate the electrical performance of a TFT, such as on/off current ratio, subthreshold swing (SS), threshold voltage (\(V_T\)), carrier mobility (\(\mu\)), and total trap density (\(N_T\)). In this work, the IGO TFT exhibits a high-performance with a large on/off ratio of \(1.21 \times 10^6\) and a small subthreshold swing of 0.41 V/dec, respectively. A threshold voltage of 0.9 V was calculated from the y-axis intercept of the square root of \(I_D\) versus \(V_G\) plot, indicating full enhancement mode operation. The device mobility can be calculated from the following equation:

\[
I_D = \frac{W}{2L}C_{ox}\mu(V_G - V_T)^2. \tag{1}
\]

where \(I_D\) is the drain current under saturation region, \(W/L\) is the dimension of the device (20 in this work), \(C_{ox}\) is the gate insulator capacitance per unit area \((3.98\times10^{-8} F/cm^2\) for Al\(_2\)O\(_3\)), \(V_G\) is the applied gate bias, and \(V_T\) is the threshold voltage. On the other hand, the subthreshold swing is defined as:

\[
SS = \frac{\partial V_G}{\partial \log I_D}. \tag{2}
\]

In order to investigate the UV-sensing ability, the fabricated IGO TFT was then exposed to the light with wavelength of 600 nm to 240 nm. Figure 6 shows the transfer curves of the IGO TFT in the dark and under illumination. The mechanism of a phototransistor can be explained as the phenomenon of band bending in the channel region caused by photo-excited carriers, which could offset the threshold voltage or cause reduction in injection barrier for carriers from source to drain,\(^{16,27-29}\) When the TFT is under illuminated, the drain current \((I_D)\) is composed of the initial current flow \((I_0)\) caused by the
applied electric field and the photo-induced current (IPh) originated from the photo-generated electrons. As shown in Figure 6, while the photon energy increases, the off-state drain current increases significantly, however, the on-state current only increases a little. While the device is operated at off state, the drain current is dominated by photo-induced current; on the other hand, when at on state the initial current will dominate. Figure 7 shows the current-voltage results in the dark and under 300-nm illumination with V_G increased from 0 V to 10 V by a step of 2 V. It is observed that the TFT showed higher drain current after being illuminated.

Here, we introduce three important parameters to quantify the performance of a UV sensor, which are responsivity (R), rejection ratio (RR), and external quantum efficiency (η, EQE). Responsivity is the generated photocurrent per unit incident UV light power, defined as:

$$R = \frac{I_D - I_{\text{DARK}}}{P_{\text{inc}}} \quad \text{(A/W)}, \tag{3}$$

where I_DARK is the dark current and P inc is the power of incident light. The rejection ratio, indicating how a detector rejects the interference of the visible radiation, is defined as the responsivity at 240 nm divided by that at 600 nm. The external quantum efficiency is described as in Equation 4:

$$\eta = \frac{R \cdot h \cdot c}{q \cdot \lambda}, \tag{4}$$

where h is the Plank’s constant, c is the speed of light, q is the charge of an electron, and λ is the wavelength of the UV light used. Figure 8 shows the spectral responses of the IGO TFT. An apparent peak at roughly 450 nm is observed, which is caused by bcc-In_{2}O_{3} in the film that we have mentioned above. The responsivity, RR, and EQE were 5.012 A/W, 1.65 × 10^5, and 25.94, respectively. Moreover, Table I summarizes the performance of some previous reports in the literature. The result suggests that InGaO is a promising semiconductor candidate for UV-detection application in the future.

| Material     | Responsivity (A/W) | Quantum Efficiency (%) | Rejection Ratio | Reference |
|--------------|--------------------|------------------------|-----------------|-----------|
| In_{0.7}Zn_{0.3}O | <0.1               | ~10                    | -               | 24        |
| InGaZnO      | 0.44               | ~200                   | ~10^2           | 15        |
| InTiZnO      | 2.3                | 938                    | 1.8 × 10^3      | 17        |
| InGaO        | 5.012              | 2594                   | 1.65 × 10^5     | This work |

Conclusions

In this work, the optical-electrical properties of IGO TFT with channel layer thickness of 20 nm is explored in detail. The room-temperature sputtered IGO thin films demonstrated an average optical transmittance of 80% in the visible light region with a relatively large bandgap of 3.63 eV. The IGO TFT shows a threshold voltage of roughly 0.9 V, mobility of 2.66 cm²/Vs, on-off ratio of 1.21 × 10^6, and SS of 0.41 V/dec, respectively. The devices show remarkable electrical properties due to high gate capacitance, low series resistance, and the improved film quality obtaining by ALD method. On the other hand, the IGO TFT shows an excellent responsivity of 5.012 A/W under 240-nm illumination at −18 V. The high rejection ratio of 1.65 × 10^5 also indicates that the TFT is good at recognizing UV light and visible light. These results indicate that IGO can be used as a high-performance UV-sensor.
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