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# Ultraviolet Photodetection Application in Magnesium Indium Oxide Thin Film Transistors via Co-Sputtering Deposition

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**Abstract:** A magnesium-doped indium oxide ( $In_2O_3$ :Mg) ultraviolet (UV) thin film phototransistor was fabricated via cosputtering of MgO and  $In_2O_3$ . Three samples with different sputtering power values of  $In_2O_3$  ranging from 40 to 60 W, namely, sample A with 40 W, sample B with 50 W, and sample C with 60 W, were used in this study. Results confirmed that oxygen vacancy concentration evidently indicates indium content. The experimental results showed that responsivities of samples, defined as the ratio of photocurrent under illumination per input power, increase from 0.0086 to 2.6 A/W. Rejection ratios were  $1.2 \times 10^4$ ,  $4.3 \times 10^5$ , and  $4.8 \times 10^5$  for samples A, B, and C, respectively. Based on our results, sample C is the best among the three MgInO UV phototransistors investigated in this study.

Keywords: phototransistor; magnesium doping indium oxide; cosputtered

# 1. Introduction

Thin film transistors (TFTs) are widely used in various applications, such as active matrix organic light-emitting diodes, active matrix liquid crystal, and flat panel displays. Oxide-based TFTs have the advantages of reasonable mobility, high transparency, low processing temperature, amorphous phase, and high uniformity for flexible substrates or large-area production. Both electrical and optical properties of oxide-based TFTs can be bandgap engineered by the doping method, and their cutoff wavelength can be easily tuned by alloying them with other oxide semiconductors. Oxide semiconductor detectors are used for ultraviolet (UV) detection due to their wide bandgap of >3 eV, high breakdown field, and thermal stability. Thus, oxide semiconductors are promising materials for phototransistors. Phototransistors can integrate light detection and signal magnification properties in one device due to their high sensitivity, low noise, low cost, and easy fabrication [1,2]. Accordingly, phototransistors have various potential applications, such as optoisolators, optical switches, and retrosensor circuits with voltage-switching capability [3–5]. Among them, UV detection is of utmost importance because of its specific applications, such as flame detection, short-range communication, and UV astronomy [6]. However, commercial silicon-based UV detectors are limited by high leakage current due to their narrow bandgap and requirement of expensive wood filters that are unsuitable for UV detecting [7]. Visible- ( $\lambda \le 400$  nm) and solar- ( $\lambda \le 280$  nm) blind phototransistors can be divided on the basis of the cutoff wavelength, which has three regional classifications, namely,



UV-A (400–320 nm), UV-B (320–280 nm), and UV-C (280–10 nm) [8]. The visible- or solar-blind phototransistor requires a wide bandgap. Metal oxide semiconductors are promising materials for UV light detection sensors.

Metal oxide semiconductors with wide bandgap (>2 eV) demonstrate intrinsic visible blindness, high chemical bonding strength, and simple fabrication properties, which are suitable for UV-light detection [9]. Among them,  $In_2O_3$ -based materials are used in UV phototransistors.  $In_2O_3$  is a high mobility and wide bandgap n-type material typically used as carrier supplier in metal oxide-based semiconductors. Oxygen vacancies are major defects of  $In_2O_3$  that produce two free electrons as donors [10]. However, the excessively large number defects can lead to high visible light sensitivity and high off-stead current in  $In_2O_3$  TFTs and the doping behavior can be a function of carrier suppressors in the active layer. Park et al. reported the improved performance of lanthanum indium zinc oxide (La-IZO) TFTs using radio frequency cosputtering by controlling the sputtering power applied to the La target. Compared with electronegativity values of indium (1.78), zinc (1.65), and oxygen (3.44), the lower electronegativity value of lanthanum at 1.1 results in a strong ionic bond between La and O due to the large difference in their electronegativity values [11]. Park et al. [12] investigated the incorporation of gadolinium into IZO TFTs and demonstrated that the formation of stable Gd–O ionic bonds due to the large difference in electronegativity values between Gd and O can improve the device performance of Gd-IZO TFTs and Gd can be used as an element of carrier suppressor. Choi et al. [13] assessed the carrier-suppressing effect of Sc in InZnO systems applied to TFTs and used Sc as the carrier suppressor to control oxygen vacancies effectively and supply free electrons due to its low standard electrode potential (SEP) (-2.36) and lower electronegativity (1.3) than oxygen (3.4).

Compared with indium and oxygen, the higher electronegativity values of the Mg element (1.2) can reduce the defect by forming oxygen vacancies [14]. Furthermore, MgO is suitable for solar-blind photodetection because of its transparent semiconductor with a wide bandgap of ~7.8 eV and ability to remain physically and chemically stable at high temperatures [15]. Electrical properties of  $In_2O_3$  TFTs can be improved and bandgaps engineered via MgO doping and tuning the composition of MgO and  $In_2O_3$  in the active layer. In this work, the cosputtered method was applied to the fabricated MgInO phototransistor to modulate the power of the  $In_2O_3$  target, change the vacancy concentration, and engineer the cutoff wavelength. Electrical and photo properties of devices are discussed in the following section.

#### 2. Experiment and Device Fabrication

The fabricated device comprises a bottom gate, dielectric layer, active layer, and Source/Drian (S/D) electrode. Three samples with various In<sub>2</sub>O<sub>3</sub> target power values, namely, samples A, B, and C with 40, 50, and 60 W, respectively, were used in this study. First, heavily doped p-type silicon was cleaned with acetone, methanol, and water using an ultrasonic cleaner for 10 min in order to clean grease and particles from the glass. The p<sup>++</sup> silicon wafers served as a bottom gate and used for growing a 300 nm thickness of SiO<sub>2</sub> dielectric layer. After that, the active layer deposition 30 nm thick MgInO thin film used MgO and  $In_2O_3$  targets by the cosputtering method with an interdigitated shadow mask. MgO target power was fixed at 100 W; the  $In_2O_3$  target power was 40, 50, and 60 W for samples A, B, and C, respectively. Before opening the shutters, the targets were presputtered for 5 min to remove the impurities in the target surface. The sputtering time was carefully controlled to ensure the thin film thicknesses were equal, and that precision of sputtering power was maintained  $\pm 1$  W. The working pressure was 0.8 Pa at an argon flow of 3 sccm at room temperature. Samples were then annealed at 300 °C for 1 h in argon ambient. Finally, thermal evaporation with an interdigitated shadow mask was performed using a 100 nm source and drain electrode. The channel width and length were 1000 and 100 µm, respectively. The photo and electric properties were measured in the dark region using Agilent B1500A and 150 W Xenon lamps (Agilent Technologies, Santa Clara, CA, USA), respectively. Glancing incidence angle X-ray diffractometry (GIAXRD) (XRD, D8 Discover, Bruker, Billerica, MA, USA) and

X-ray photoelectron spectroscopy (XPS) (PHI 5000 VersaProbe, ULVAC, Chigasaki-shi, Japan) were applied to assess the crystal structure and determine the concentration of oxygen vacancy, respectively.

#### 3. Results

Figure 1a,b show the GIAXRD spectra of samples A, B, and C, and the magnified picture of the (311) diffraction line in the MgIn<sub>2</sub>O<sub>4</sub> phase. Samples A and B demonstrate significant amorphous phases and inconspicuous peaks located at  $2\theta = 32.5^{\circ}$ , which correspond to the spinel MgIn<sub>2</sub>O<sub>4</sub> (311) phase [16]. Clear diffraction peaks in Sample C indicate its polycrystalline structure and its signal may be attributed to the In<sub>2</sub>O<sub>3</sub> cubic structure (JCPDS Card No. 76-0152), which corresponds to <221>, <222>, <400>, <441>, <440>, <611>, and <622>; the In<sub>2</sub>O<sub>3</sub> cubic structure (JCPDS Card No. 06-0416), which corresponds to <521>; and the MgIn<sub>2</sub>O<sub>4</sub> spinel structure (JCPDS Card No 40-1402) which corresponds to <541>. Transfer characteristic curves of MgInO TFTs were measured under V<sub>DS</sub> = 10 V and a range of V<sub>GS</sub> = -30 to 20 V, as shown in Figure 2. Table 1 presents the electric performance of three samples, including threshold voltage, field effect mobility, subthreshold swing, and on/off ratio. Carrier mobility can be calculated as follows [17]:

$$I_{DS} = \frac{W}{2L} C_i \mu_{sat} (V_{GS} - V_{TH})^2 \tag{1}$$

where W and *L* are the width and length of the channel, respectively; *Ci* is the capacitance of the dielectric layer per unit area;  $\mu_{sat}$  is the field effect mobility; and  $V_{th}$  is the threshold voltage. Mobility increased from 0.134 to 2.01 cm<sup>2</sup>/V-s when In<sub>2</sub>O<sub>3</sub> content increased. The threshold voltage shifted in the negative direction, likely due to the increase in number of oxygen vacancies as the donor in the MgInO material system. In addition, the threshold voltage is defined from the linear extrapolation of  $I_{DS}^{1/2}$  versus  $V_{GS}$ . The intersection of the linear extrapolation and the *x*-axis is the V<sub>TH</sub> value. S.S is the change in gate voltage needed to increase the drain current by one order of magnitude with respect to the switching speed of the device, and can be expressed as follows:

$$S.S = \frac{\partial V_{GS}}{\partial (\log I_{DS})} \tag{2}$$

S.S decreased from 2.59 to 1.81 V/decade and then increased to 2.83 V/decade, likely due to grain boundaries and other defects that act as carriers for scattering and trapping sites. Thus, gate controllability deteriorated and the gate insulator would likely be damaged because of the large sputter power of sample C. Moreover, the on/off ratio of samples was at approximately  $10^5$ . However, when raising the In<sub>2</sub>O<sub>3</sub> power from 70 W, however, greater In<sub>2</sub>O<sub>3</sub> leads to high conductivity performance with no transfer characteristic. It is also worth noting that each measurement was repeated three times; the deviation value was less than 1% and there were differences between the three groups on the same variable.



**Figure 1.** (**a**) Glancing incidence angle X-ray diffractometry (GIAXRD) spectra of three samples. (**b**) The magnified picture of the (311) diffraction line of the MgIn<sub>2</sub>O<sub>4</sub> phase.



Figure 2. Logarithmic and linear scale of transfer characteristic curves for samples (a) A, (b) B, and (c) C.

	Threshold Voltage (V)	$\mu_{FE}$ (cm <sup>2</sup> /Vs)	S.S (V/dec)	On/Off Ratio
Sample A	13.2	0.134	2.59	$2.2 \times 10^{5}$
Sample B	-0.88	0.25	1.81	$6 \times 10^{5}$
Sample C	-12.2	2.01	2.83	$1.4 \times 10^5$

Table 1. Electric properties of MgInO under different target power values of  $In_2O_3$ .

11,	$\mu_{FE:}$ is the fi	ield effect mobility;	S.S is the sub	threshold swing.
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Figure 3 shows the output characteristic curves under different gate voltages from 0 to 10 V. The increasing drain current and off-current of the device as gate voltages increase demonstrate the operational modes of n-channel TFTs. The conductivity of the channel layer increased due to the increase in sputtering power of indium oxide. The high sputtering power of indium oxide increases the carrier concentration in the thin film.

Figure 4 showed XPS and fitting spectra of O 1s deconvolution with Gaussian function confirms the concentration of oxygen vacancy in the thin film, the detail values were summarized in Table 2. The three peaks, M–O, Vo, and M–OH, can be attributed to  $O_2^-$  ions in metal oxide lattices, oxygen vacancies, and M–OH compounds on the surface, respectively [18]. Magnesium content is from 17.5 to 11.56 at% and indium content is from 34.75 to 38.82 at%. Oxygen vacancies increased from 27.59 to 40.91% with the increased target power of  $In_2O_3$ . The elemental composition via XPS measurement is presented in Table 3. The priority of bonding between multimetal oxide can be explained by electronegativity, which describes the tendency for attracting electrons. Electronegativity differences in Mg–O and In–O are 2.13 and 1.66, respectively. Thus, the stronger attraction of Mg to oxygen than In results in the reduction of oxygen vacancies. MgInO thin films demonstrate good application potential in UV light detection due to their high transmittance and wide bandgap. Tauc plots of the three samples are illustrated in Figure 5 to determine the optical energy bandgap. Optical bandgap of

4.4, 4.1, and 3.65 eV for samples A, B, and C, respectively, indicate that band gaps can be engineered with different target power values of  $In_2O_3$ .



Figure 3. Measured output characteristic curves of samples (a) A, (b) B, and (c) C with different  $V_{GS}$  values.

Table 2. X-ray photoelectron spectroscopy (XPS) measurement of O 1s spectra of the three samples.

	M–O (%)	VO (%)	M–OH (%)
Sample A	54.63	27.59	17.78
Sample B	54.35	32.96	12.69
Sample C	53.15	40.91	5.94

	Mg 2p	In 3d	O 1s
Sample A	17.50	34.75	47.75
Sample B	15.08	37.06	47.86
Sample C	11.56	38.82	49.63

Table 3. Elemental composition of the three samples.



Figure 4. Fitting results of XPS spectra with O 1s peak for samples (a) A, (b) B, and (c) C.



Figure 5. Tauc plots of the three samples with different target power values.

Figure 6 shows the three samples that are measured under light illumination with wavelengths from 500 to 240 nm in an interval of 40 nm to investigate their photo properties. The transfer curve was measured using a gate voltage ranging from -40 to 40 V and  $V_{DS} = 10$  V. The photocurrent gradually increased when moving to short wavelength, the photo-induced current dominated the  $I_{DS}$ . Photo-excited holes trapped by shallow donor states (oxygen vacancies) originating from photo-generated electrons increased  $I_{DS}$  and subsequently reduced the barrier height from source to drain. Hence, the incident photon energy increased with increasing  $I_{DS}$  as  $V_{TH}$  shifted toward the negative direction.



**Figure 6.** Transfer characteristic curves of (**a**) sample A, (**b**) sample B, and (**c**) sample C under dark and 260–500 nm illumination.

Photoresponsivity of samples A, B, and C is depicted in Figure 7. Photoresponsivity can be calculated as follows:

$$R = \frac{I_{light} - I_{dark}}{P_{opt}}$$
(3)

where  $I_{light}$  is the photocurrent,  $I_{dark}$  is the dark current, and  $P_{opt}$  is the power of incident light. Notably, responsivities are calculated under  $V_{DS} = 10$  V and  $V_{GS} = -10$  V,  $V_{GS} = -20$  V, and  $V_{GS} = -38$  V for samples A, B, and C, respectively. Responsivity and rejection ratios of samples A, B, and C are 0.0086, 0.17, and 2.6 A/W, and  $1.2 \times 10^4$ ,  $4.3 \times 10^5$ , and  $4.8 \times 10^5$ , respectively. In addition, rejection ratios are defined as the responsivity at 280 nm divided by the responsivity at 460 nm. A high rejection ratio indicates that the device can distinguish between visible light and UV. The existence of oxygen vacancies deteriorates the device performance because responsivity continued to increase, although the light energy was lower than the bandgap energy, likely due to trap levels and band-tail states from the structural defect, especially in amorphous oxide [19]. A comparison of optical characteristics demonstrated that sample C exhibited the best performance due to its high mobility, which indicated the highest induced photocurrent. XPS spectra confirmed that the composition of thin films can improve the photo and electric performance of the device by controlling oxygen vacancy defects. Meanwhile, UV phototransistors with precise control over composition can enhance the device performance. Hence, the device performance with moderate oxygen or hydrogen flow can lead to the control of oxygen vacancy concentration [20–22].



**Figure 7.** Photoresponsivity of MgInO thin film transistors (TFTs) measured at  $V_{DS} = 10$  V with a wavelength range of 240–500 nm.

## 4. Conclusions

MgInO phototransistors were fabricated using the cosputtering method. The electric and photo properties of the active layer were investigated with various magnesium to indium ratios. The high correlation between electric and photo properties of MgInO TFTs and the indium content determines the device performance. However, the excessive defect caused by the formation of the  $In_2O_3$  precipitate phase in polycrystalline films can deteriorate photo and electric characteristics. The results showed that the optimized parameter is demonstrated in sample C, which obtained a responsivity and UV-to-visible rejection ratio of 2.6 A/W and  $4.8 \times 10^5$ , respectively.

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