

# High Mobility Oxide TFT Based on In-rich In-Ga-Sn-O Semiconductors with Nanocrystalline Structures

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## ABSTRACT

*In-rich In-Ga-Sn-O film with nanocrystalline structure was prepared as the active layer for high mobility TFT. The prepared top-gate self-aligned TFTs using the IGTO film deposited at low O<sub>2</sub> gas ratio and low power exhibited excellent transfer characteristics with high mobility of 25.33cm<sup>2</sup>/Vs, ss of 0.33V/decade, threshold voltage of 0.98V.*

## 1 INTRODUCTION

In recent years, thin film transistors (TFT) based on metal oxide semiconductors (MOS) have attracted more and more attentions in display market due to the high mobility, low off current, large area and low temperature fabrication [1]. To achieve high resolution and high frame rate displays, the TFTs with high mobility are studied widely through optimizing the compositions of metal oxide materials such as In-Zn-Sn-O [2], In-Ga-Zn-Sn-O [3], In-Ga-O [4] and In-Zn-W-O [5]. It is well known that In and Sn cations with the [Kr]4d<sup>10</sup>5s<sup>0</sup> electronic configuration exhibit large spatial overlap between the 5s orbitals and afford high conductive paths to electron carriers, leading to high electron mobility. In addition, the Ga cation which could form strong bonds with oxygen anions and inhibit the occurring of oxygen vacancies are frequently added as suppression of excess charge carriers [6]. Generally, it is an effective means to increase the mobility by raising the ratios of In and Sn elements in metal oxide materials. However, the metal oxide materials with high In proportion are tend to crystallize, forming polycrystalline structures [7]. The polycrystalline structures could reduce the uniformity of G4.5 glass. Moreover, the grain boundaries could disturb the carrier transportation as scattering centers and decrease the electron mobility[4].

In this paper, the crystal performance of In-rich IGTO films was firstly studied. It was found that the film thickness, O<sub>2</sub> ratio and power during deposition were the important factors. As the O<sub>2</sub> gas ratio, deposition power and film thickness increased, the crystallinity of IGTO thin film increased. Then the top-gate self-aligned (TGSA) In-rich In-Ga-Sn-O (IGTO) TFTs were fabricated and investigated. A high mobility was achieved mainly due to the high ratio of In element in metal oxide semiconductor target. The results showed that the electrical performance of TGSA In-rich IGTO TFT would become worse with the increase of the crystallinity of IGTO thin film. In addition, the TGSA TFTs using the IGTO film deposited at low O<sub>2</sub> gas ratio and low power with a W/L of 10μm/10μm exhibited a high mobility of 25.33 cm<sup>2</sup>/Vs, ss of 0.33 V/decade, threshold voltage (V<sub>th</sub>) of 0.98 V.

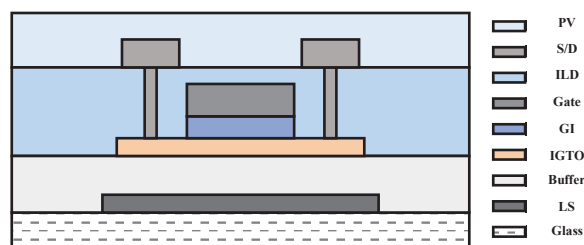
## 2 EXPERIMENT

The IGTO thin films were deposited by DC magnetron sputtering at room temperature with a thermal annealing. We investigated the effects of O<sub>2</sub> gas ratio, deposition power and film thickness on the crystal of IGTO thin films, and the detail conditions can be seen in table 1.

**Table 1 The detail conditions of IGTO thin film deposition**

Sample	Conditions		
	Low O <sub>2</sub>	Medium O <sub>2</sub>	High O <sub>2</sub>
Power	Low power		High power
Film thickness(nm)	30	60	100

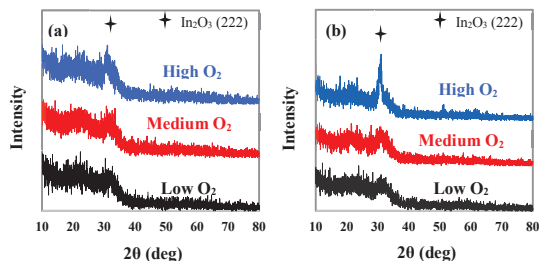
The top-gate self-aligned (TGSA) In-rich In-Ga-Sn-O (IGTO) TFTs were fabricated on G4.5 glass and the structure diagram is showed in Fig. 1. A light-shielding (LS) metal was deposited and patterned on the substrate firstly. A SiO<sub>x</sub> buffer layer was subsequently deposited using plasma enhanced chemical vapor deposition (PECVD). IGTO film layer was sputtered and patterned as the channel layer. SiO<sub>x</sub> layer was deposited by PECVD as the gate insulator (GI). Mo/Al/Mo metal layers were deposited using DC sputtering as the gate layer. Gate and GI layer were continuously patterned to form top-gate self-aligned structure. Then a plasma treatment was applied for creating n+ IGTO S/D ohmic contact. After that, a SiO<sub>x</sub> layer was deposited as inter-layer dielectrics deposition (ILD). Mo/Al/Mo metal layers were deposited and patterned as the source (S) and drain (D). Devices fabrication were finished by passivation (PV) layer deposition. An Keithley 4200-SCS semiconductor parameter analyzer was used to measure device electrical properties in the dark under ambient condition. X-ray diffraction (XRD) analysis was carried out using Cu-Kα radiation (40 kV, 30mA).



**Fig. 1 The structure diagram of top-gate self-aligned IGTO TFT**

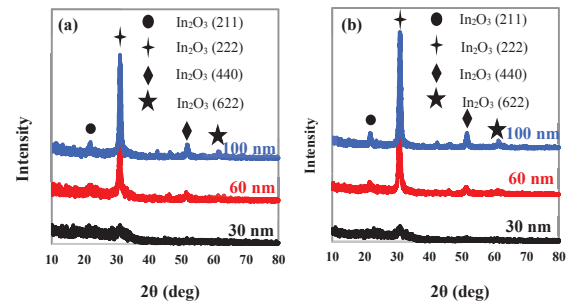
### 3 RESULTS and DISCUSSION

This section describes the detailed guidance for preparing figures and tables in the manuscript. Firstly, we investigated the crystal performance of IGTO thin films deposited at different O<sub>2</sub> gas ratios and powers. X-ray diffraction (XRD) spectra of IGTO films with different O<sub>2</sub> gas ratios deposited at (a) low power and (b) high power are showed in Fig. 2, and the film thickness of the IGTO are 30 nm. It could be seen that the XRD spectrums all showed peaks nearly at 31°, which were inferred from (222) plane of In<sub>2</sub>O<sub>3</sub> structures due to higher Indium ratio. It could be seen in Fig.4(a), the Nanobeam Electron-Diffraction (NED) patterns of the IGTO thin film deposited at low O<sub>2</sub> gas ratio showed diffraction rings composed with many bright diffraction spots, indicating an aggregate of nanosized fine crystals of IGTO. As the increasing of O<sub>2</sub> gas ratios, the diffraction peaks became sharper in Fig. 2, indicating that the crystallinity of IGTO thin film increased. This phenomenon can also be certified by the NED pattern in Fig.4 (b), in which the NED pattern appeared obvious diffraction spots derived from (222) plane besides the diffraction rings. Especially, the higher concentration of reactive oxygen (atomic and excited molecular oxygen) improved the oxidation of the metal atoms on the film surface, causing the appearance of indium oxide phase with nanocrystalline. At even higher oxygen flows the indium oxide phase rapidly appears and develops into large crystallites[8]. It had also been reported that the crystal of IGZO required high O<sub>2</sub> gas ratio during the deposition [9]. Diffraction peaks of SnO<sub>2</sub> were never found, which is in accordance with the result of Frank and Köstlin, that Sn can be solved in In<sub>2</sub>O<sub>3</sub>[10].



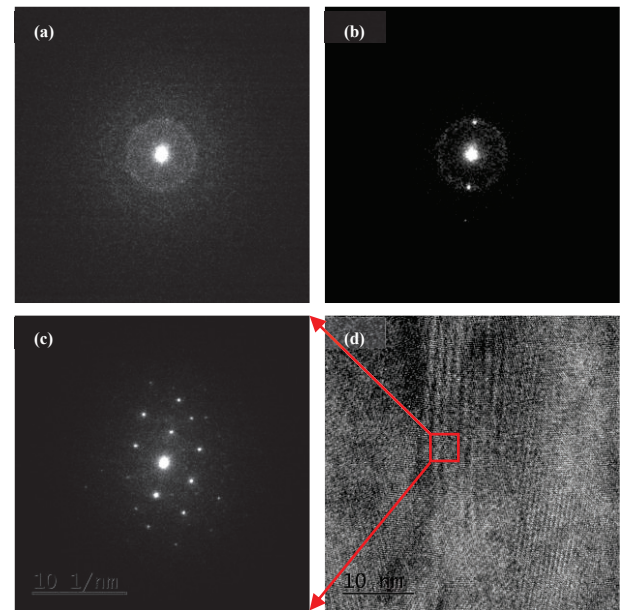
**Fig. 2 X-ray diffraction (XRD) spectrums of IGTO films with different O<sub>2</sub> gas ratios deposited at (a) low power and (b) high power**

In addition, it can be seen in Fig. 2(b) that the crystallinity of IGTO thin film increased similarly with the increase of O<sub>2</sub> gas ratio for the high power deposition. Especially, this tendency is much more obvious for the high power deposition. As the increase of the deposition power, the kinetic energy of the sputtered atoms arriving at the film surface increased leading to the more sufficient crystallization through the growth and coalescence of grains.



**Fig. 3 X-ray diffraction (XRD) spectrums of IGTO with different film thickness deposited at (a) low power and (b) high power**

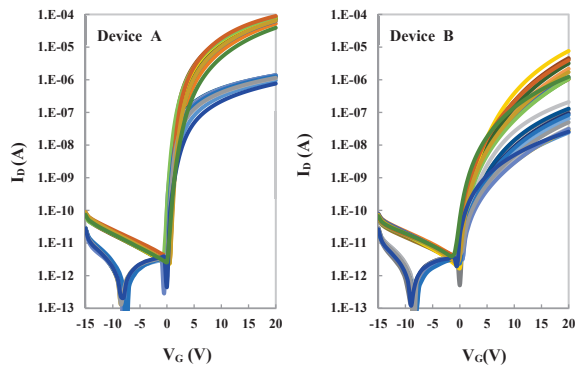
Fig.3 showed the XRD spectrums of IGTO thin films with different film thickness deposited at (a) low power and (b) high power. Several sharp peaks are observed for 60 nm and 100 nm IGTO thin films near the 22°, 31°, 52° and 62°, which are inferred from In<sub>2</sub>O<sub>3</sub> structures due to higher Indium ratio. When the film thickness increased from 30 nm to 100 nm, the IGTO thin film transition from nanocrystalline structure to polycrystalline structure, indicating the enhancement of crystallinity.



**Fig. 4 Nanobeam Electron-Diffraction (NED) patterns of IGTO thin films with thickness of 30 nm deposited at (a) low O<sub>2</sub> and (b) high O<sub>2</sub>, (c)NED pattern and (d) High-resolution cross-sectional TEM image of IGTO thin film with thickness of 100 nm**

Fig. 4 (c) and (d) showed the NBD pattern and high-resolution TEM image of the IGTO thin film with thickness of 100 nm, respectively. A crystal lattice in order to the IGTO surface was observed in the high-resolution TEM image, and the main diffraction spots derived from (222) plane and others were seen in the NBD pattern. This behavior reflected the further grain growth after the first nucleation period and the

coalescence of the grains with increasing the deposition time, leading to the increase of grain size and crystallinity.



**Fig. 5 Transfer characteristics of TGSA IGTO TFTs with (Device A) low O<sub>2</sub> gas ratio and (Device B) high O<sub>2</sub> gas ratio of IGTO thin film deposition**

We fabricated top-gate self-aligned (TGSA) TFTs using the 30 nm In-rich IGTO thin film as the active layer by sputtering at low power with high O<sub>2</sub> gas ratio and low O<sub>2</sub> gas ratio, and evaluated the electrical characteristics of these TFTs. Fig. 5 showed the ID-VG curves of the TFTs at the drain-to-source voltages V<sub>ds</sub> = 0.1 and 10 V. The device A with low IGTO deposition O<sub>2</sub> gas ratio exhibit excellent transfer characteristics as seen in Table 2, such as a high mobility of 25.33 cm<sup>2</sup>/Vs, ss of 0.33 V/decade, threshold voltage (V<sub>th</sub>) of 0.98 V. However, the device B with high IGTO deposition O<sub>2</sub> gas ratio showed poor electrical characteristics, and the uniformity on G4.5 glass was worse than device A. As mentioned in Fig. 2 and Fig. 4, as the O<sub>2</sub> gas ratio of the IGTO thin film increased, the crystallinity and crystal boundaries of IGTO thin film increased. The grain boundaries are responsible for the scattering of carriers and create a potential barrier that restricts the flow of charge carriers from grain to grain, resulting the deterioration of electrical characteristics [11]. On the other hand, the oxygen vacancy in the IGTO thin film could be filled up when increasing the O<sub>2</sub> gas ratio during the deposition. Therefore, the concentration of carries reduced and resulting in a decrease of mobility and current. In addition, the poor uniformity of crystal influence the uniformity of electrical performance, especially for the high deposition O<sub>2</sub> gas ratio of IGTO thin fim.

**Table 2 The electrical parameters of device A and B**

Device	Mobility(cm <sup>2</sup> /Vs)	SS(V/decade)	V <sub>th</sub> (V)	ΔV <sub>th</sub> (V)
A	25.33	0.33	0.98	0.69
B	2.44	0.74	2.44	1.74

#### 4 CONCLUSIONS

In-rich In-Ga-Sn-O (IGTO) film with nanocrystalline structure was prepared by sputtering easily at different O<sub>2</sub> gas ratio and power during the deposition. As the O<sub>2</sub> gas ratio, deposition power and film thickness increased, the crystallinity of IGTO thin film increased. Especially, the electrical performance of TGSA In-rich IGTO TFT would deteriorate with

the increase of the crystallinity of IGTO thin film. The prepared top-gate self-aligned TFT based on the nanocrystalline IGTO film deposited at low O<sub>2</sub> gas ratio and low power exhibited a high mobility of 25.33 cm<sup>2</sup>/Vs, ss of 0.33 V/decade, threshold voltage (V<sub>th</sub>) of 0.98 V. It is worth to mention that the polycrystal structure of IGTO thin film should be prevented so as to achieve high mobility and uniformity. The TGSA IGTO TFT with a high mobility is a promising technology which can applied as the backplane for advanced display.

#### 5 Acknowledgment

The first and second authors contributed equally to this work.

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