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Fabrication of IGZO Sputtering Target and Its Applications to the Preparation of Thin-film Transistor (TFT) Devices

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A hybrid of chemical dispersion and mechanical grinding process was developed to fabricate the mixture of nano-scale In_2O_3, Ga_2O_3 and ZnO oxide powders at the atomic ratio 1:1:2. As revealed by *x*-ray diffraction (XRD) analysis, sputtering target containing sole $IGZO_4$ phase could be obtained by sintering the oxide mixture pressed in disc form at temperatures ≥ 1300°C for 6 hrs. The IGZO target was then transferred to a sputtering system and the thin-film transistors (TFTs) containing amorphous IGZO channels were fabricated. Post-annealing at 300°C for 1 hr in air ambient was performed in order to improve the device performance. Electrical measurements indicated that the TFT samples with saturation mobility (μ_{sat}) = 14.7 cm^2/V·s, threshold voltage (V_{TH}) = 0.57 V, subthreshold swing (S.S.) = 0.45 V/decade and on/off ratio = 10^8 could be achieved.

Introduction

Transparent amorphous oxide semiconductors (AOSs) are promising materials for channel layer of thin-film transistors (TFTs) because AOS TFTs exhibit a relatively high saturation mobility (μ_{sat} >10 cm^2/V·s), high film flatness, low processing temperatures and high optical transparency in the visible region [1]. However, some AOS materials have uncontrollable carriers generated due to the presence of oxygen vacancies. Therefore, it is crucial to develop an appropriate AOS material with satisfactory physical properties and stable charge carrier feature to fulfill practical applications. Recently, amorphous In-Ga-Zn-O (a-IGZO) thin films for channel layer of transparent TFTs have attracted a lot of attentions due to their unique physical properties and processing advantages [2]. The a-IGZO channel layer prepared *via* sputtering deposition process demonstrates its feasibility to large-area TFT device fabrication [3]. The dependence of the TFT characteristics on the elemental composition of IGZO has been investigated in detail [4]. In this study, we reported the preparation of sputtering target containing sole $IGZO_4$ phase by using a hybrid of chemical dispersion and mechanical grinding process. The self-made IGZO target was then utilized to fabricate the TFT devices on Si and glass substrates, respectively, and key electrical properties were measured. The deposited IGZO films was characterized by *x*-ray diffraction (XRD), *x*-ray photoelectron spectroscopy (XPS), atomic force microscopy (AFM) and UV-visible spectrometer so as to elucidate the relationship between film microstructure and TFT device performance.

Experimental

For the preparation of precursor oxide powders for IGZO target, as-received ZnO (purity = 99.999%, Seedchem/Australia) Ga_2O_3 (purity = 99.995%, ELECMAT/USA) and In_2O_3 (purity = 99.99%, CERAC/USA) powders were first rinsed in ethanol. The

In_2O_3, Ga_2O_3 and ZnO powders were mixed at the molar ratio = 1:1:2 and a hybrid of chemical dispersion and mechanical grinding process [5] was then carried out to fabricate the aqueous suspension containing nano-scale In_2O_3, Ga_2O_3 and ZnO oxide powder mixture. After drying, the powder mixture was pressed into disc form and consequently sintered at temperatures ranging from 900 to 1400°C for various time spans so as to identify the condition for $IGZO_4$ phase formation. The self-made IGZO target was transferred into a sputtering system and the TFT devices containing 15-nm thick amorphous IGZO channels were fabricated on n^+-Si substrate containing 200-nm thick thermal oxide layer and glass substrates, respectively. The sputtering was carried out at a Ar/O_2 gas flow ratio = 20/1.2, RF power = 80W and working pressure = 1 mtorr. 300-nm thick aluminum (Al) metal lines deposited by *e*-beam evaporation served as the source and drain electrodes of devices. Finally, the annealing treatments at temperatures of 300°C for 1 hr in air ambient were performed in order to improve the device performance.

Results and Discussion

By sintering the In_2O_3, Ga_2O_3 and ZnO powder mixtures at temperatures ranging from 900 to 1400°C for various times, it was found that the sole $IGZO_4$ phase could be obtained *via* a sintering at temperatures ≥ 1300°C for 6 hrs. Figure 1 presents the XRD patterns of the powder mixtures before and after the 1300°C/6-hr sintering treatment and it illustrates the presence of $IGZO_4$ phase in the self-made target in accord with the JCPDS-381104 standard.

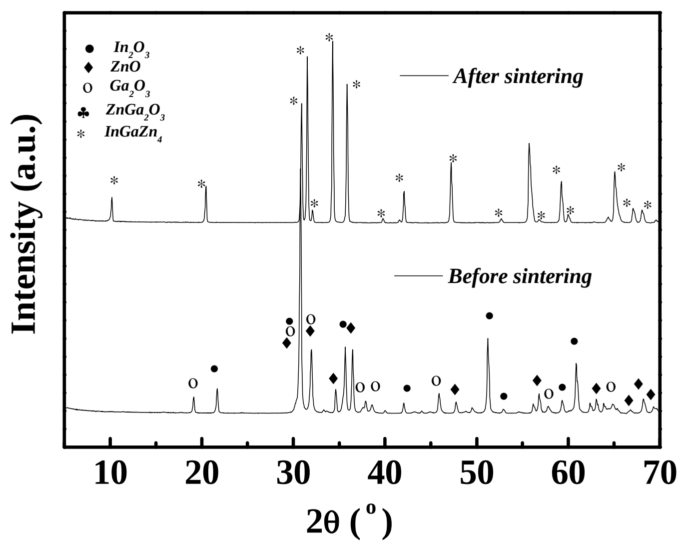

Figure 1. XRD patterns of In_2O_3, Ga_2O_3 and ZnO powder mixture before and after the 1300°C/6-hr sintering treatment.

Sputtering deposition was performed by using the self-made IGZO target and the XRD pattern of a 100-nm thick IGZO film subjected to a heat treatment at 300°C for 1 hr is shown in Fig. 2. It indicates the IGZO film remains amorphous even though it has been heated in such a high-temperature ambient. A cross-sectional TEM (XTEM) micrograph of 15-nm thick IGZO channel layer in TFT sample is displayed in Fig. 3. The selected area electron diffraction (SAED) pattern taken from the vicinity of IGZO region shows vague diffraction rings, again illustrating the amorphous feature of IGZO layer. Further, the IGZO film exhibits a very smooth surface with an average roughness ≈ 0.15 nm as revealed by AFM characterization.

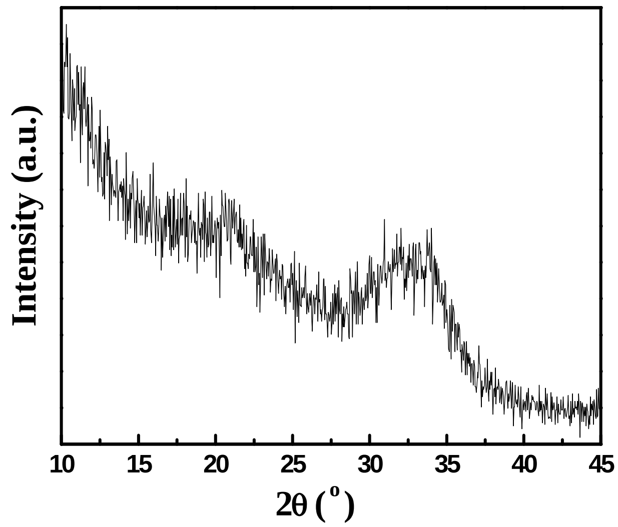

Figure 2. XRD of IGZO films deposited by using the self-made IGZO target. The film is about 100-nm thick and is subjected to a heat treatment at 300°C for 1 hr.

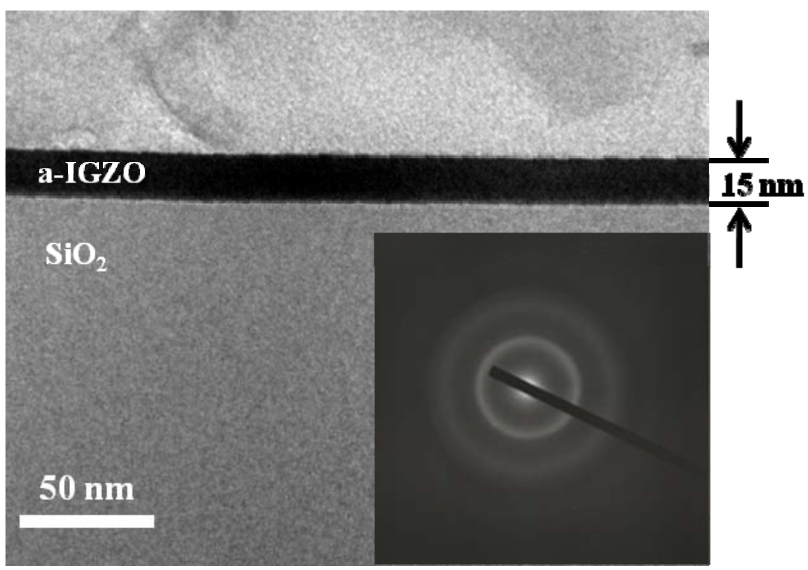

Figure 3. XTEM micrograph of 15-nm thick IGZO channel in a TFT sample made on Si substrate.

Figure 4 shows the transmittance of IGZO film subjected to the 300°C/1-hr post-annealing. It indicates that the film possesses an average transmittance ≥ 85% in the visible-light wavelength range, illustrating its high optical transparency. There are two crucial properties of transparent conducting oxides (TCOs), *e.g.*, transparency and conductivity. The result shown in Fig. 4 hence implies the feasibility of IGZO films for fully transparent TFT fabrication.

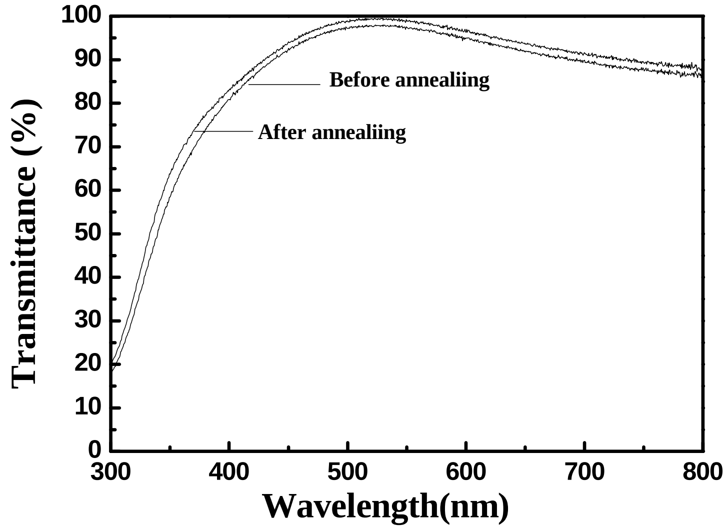

Figure 4. Transmittance of IGZO film subjected to the 300°C/1-hr post annealing.

Electrical characteristics of TFT samples were measured by using a semiconductor parameter measurement system containing a Keithley 4200 *I-V* source meter. The saturation mobility (μ_{sat}) and threshold voltage (V_{th}) were derived from a linear fitting of $\sqrt{I_{DS}}$ *versus* V_{GS} plot (I_{DS} = source to drain current; V_{GS} = gate to source voltage) using the equation

$$I_{DS} = \left(\frac{\mu_{sat} W \varepsilon_o \varepsilon_r}{2Ld} \right) (V_{GS} - V_{th})^2$$

where ε_o = dielectric constant of vacuum, ε_r = relative dielectric constant of the gate insulator (= 3.9 for SiO_2), L = device channel length, W = device channel width and d = the gate insulator thickness [6]. In this work, L = 0.1 mm and W = 1.6 mm, respectively.

Figure 5 shows the transfer characteristics of the a-IGZO TFTs before and after 300°C/1-hr post annealing at the drain to source voltages (V_{DS}) ranging from 5V to 15V. It can be seen that the TFT sample without post-annealing possesses μ_{sat}= 1.2 $cm^2/V\cdot s$, V_{th} = 1.92 V, subthreshold swing (S.S.) = 0.85 V/decade and on/off ratio = 5×10^4. Post annealing dramatically improved TFT device performance that μ_{sat} = 14.7 $cm^2/V\cdot s$, V_{th} = 0.57 V, S.S. = 0.45 V/decade and on/off ratio = 10^8 were observed. Analytical results presented above illustrate not only the good electrical performance of TFT devices prepared by using the self-made IGZO sputtering target, but also the benefits of post annealing on property improvement. It is believed that the post-annealing treatment remedies the oxygen-deficiency and amplifies the semiconductor features of IGZO layers so as to improve the electrical properties.

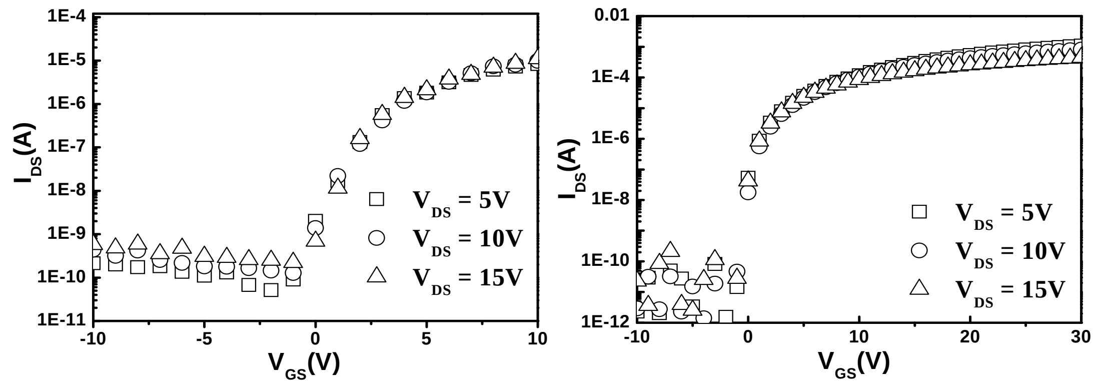

Figure 5. Transfer characteristics of a-IGZO TFTs (a) before and (b) after the post annealing at 300°C for 1 hr (V_{DS} = 5V to 15V).

In summary, mixture of nano-scale In_2O_3, Ga_2O_3 and ZnO oxide powders was prepared by a hybrid of chemical dispersion and mechanical grinding process. The powder mixture was then pressed and sintered at 1300°C for 6 hrs to form the sputtering target containing sole $IGZO_4$ phase. The target was utilized to deposit the channel layer of TFTs and XRD and TEM characterizations revealed that the amorphous IGZO films can be successfully made by using the self-made sputtering target. The a-IGZO layer possesses high optical transmittance (≥ 85%) and is feasible to fully transparent TFT fabrication. Electrical property measurement showed that the TFT device subjected to 300°C/1-hr post annealing exhibits good transfer characteristics with μ_{sat}= 14.7 cm^2/V·s, V_{th} = 0.57 V, S.S. = 0.45 V/decade and on/off ratio = 10^8.

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