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ARTICLE

Effect of Sputtering Pressure on Surface Roughness, Oxygen Vacancy and Electrical Properties of a-IGZO Thin Films

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Abstract: Thin films of amorphous indium gallium zinc oxide amorphous indium-gallium-zinc-oxide (a-IGZO) were fabricated by DC magnetron sputtering. The influence of sputtering pressure on the microstructures and the electronic properties were investigated. AFM characterization on surface morphology demonstrates that the surface roughness increases with higher sputtering pressure. The oxygen vacancies of the a-IGZO films change considerably and are reduced significantly with increasing sputtering pressure, as disclosed by X-ray photoelectron spectroscopy. Both the increased surface roughness and reduced oxygen vacancy are detrimental to the performance of a-IGZO TFTs. From this point of view, the sputtering should be done at a proper pressure of 0.06 Pa in order to ensure the enhanced performance. The electron saturation mobility (μ_{sat}) and the threshold voltage (V_{TH}) of the a-IGZO TFTs are 3.32 $cm^2/(V\ s)$ and 24.6 V at such a sputtering condition, respectively.

Key words: a-IGZO; thin-film transistor; sputtering pressure; oxygen vacancy

Because of the good electrical properties, high optical transparency in the visible region, excellent uniformity and lower processing temperature, amorphous indium gallium-zinc-oxide (a-IGZO) thin-film transistors (TFTs) have been extensively investigated as an alternative to Si-based TFTs in large-scale liquid crystal displays (LCD) or transparent organic light-emitting displays (OLED) [1-3]. Many investigators have found that the performances are affected by the deposition parameters of semiconductor layer, such as the chemical components[4,5], partial oxygen pressure[6,7], deposition power[8] and active layer thickness[9,10]. Kamiya[11] described that proper compositional ratio of In:Ga:Zn is critical for the high performance of the a-IGZO TFTs. Chong[6] observed that the threshold voltage (V_{TH}) shifted in the positive direction as O_2 ratio increased. Lee[9] and Dongsik[10] reported that instability behavior under the positive and negative bias stress reduced with increasing channel thickness. Kim[8] found that the RF power affected the $I_{on/off}$ ratio of the a-IGZO TFT and the V_{TH} negatively shifted with increasing RF power. Although Jong[12] et al. indicated that the densification of the film through reducing the sputtering pressure could decrease the bulk trap density and enhance the performance of a-IGZO TFTs, the investigation on the pressure effect of the a-IGZO thin films is still lack.

In the present paper, we studied the influence of sputtering pressure on the microstructures and electrical properties of the a-IGZO thin films. It is shown that the electrical characteristics of a-IGZO TFTs, such as, the electron saturation mobility (μ_{sat}) and the threshold voltage (V_{TH}) are considerably affected by the film surface roughness and the oxygen vacancies. In brief, an appropriate sputtering pressure should be selected to optimize the properties of relevant devices.

1 Experiment

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Fig.1 shows the bottom gate staggered TFT. A heavily doped (n++) silicon wafer was used as the substrate for IGZO film deposition, and the SiO_2 layer 100 nm in thickness served as the gate dielectric. The substrates were cleaned ultrasonically in acetone, alcohol, and de-ionized water for 10 min separately. After removing the back SiO_2 using diluted HF acid, a Ni-Cu-Ni multi-layer back contact as the bottom gate electrode was deposited by the magnetron sputtering. The a-IGZO channel layer of 40 nm in thickness was deposited on the SiO_2 layer by DC magnetron sputtering at room temperature. The compound target of In_2O_3, Ga_2O_3 and ZnO (purity 99.99%, 1:1:1 mol. ratio) was used, and the sputtering power was 30 W. The oxygen partial pressure (O_2/Ar+O_2) was maintained at 2%, but three total gas flow rates of Ar and O_2, 20, 30 and 40 cm^3/min were exploited, with the sputtering pressure of 0.02, 0.06 and 0.12 Pa, respectively. 15 min pre-sputtering was done to remove any contaminant on the target surface. Then the Ni source/drain electrodes were deposited and patterned by a metal shadow mask with the W/L= 500/100 μm. The top side of the channel layer was not passivated. Finally, the samples were annealed in N_2 ambient at 200 ℃ for 1 h.

The microstructures and surface morphology of the a-IGZO films were analyzed by High Resolution Transmission Electron Microscope (HR-TEM JEM-2100F), X-ray diffraction (Shimadzu Limited XRD-7000) and Atom Force Microscopy (AFM Veeco-diInnova). The bonding configurations were examined by X-ray photoelectron spectroscopy (XPS Thermo Scientific Kα). The electrical properties of the a-IGZO films and TFTs were measured with a Hall-effect instrument (Lakeshore 7707A) and a Keithley4200-SCS semiconductor characterization system at room temperature in dark.

2 Results and Discussion

2.1 Microstructure of the IGZO film

Fig.2 shows the XRD patterns of the IGZO film deposited with different sputtering pressures. No sharp peak feature is found, indicating the amorphous nature of the thin films regardless of sputtering pressure. As an example, Fig.3a and 3b show the bright-field HR-TEM image and the corresponding selected area electron diffraction (SAED) patterns of the IGZO film deposited under a sputtering pressure of 0.06 Pa. There are only fuzzy diffraction rings in the SAED pattern, which confirms the amorphous feature of the deposited IGZO thin film.

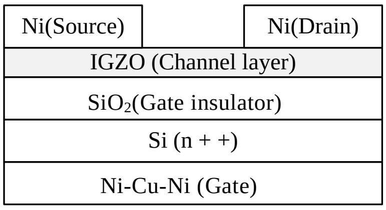

Fig.1 Schematic structure of the a-IGZO TFT

Fig.4 presents the AFM images of the surface morphology. It shows that the surface roughness of the a-IGZO film increases with the sputtering pressure, i.e., the RMS values are 0.114, 0.148 and 0.171 nm for the thin films deposited under the sputtering pressure of 0.02, 0.06 and 0.12 Pa, respectively. In fact, as the sputtering pressure increases, the bombardment of the sputtering Ar^+ on the target atoms

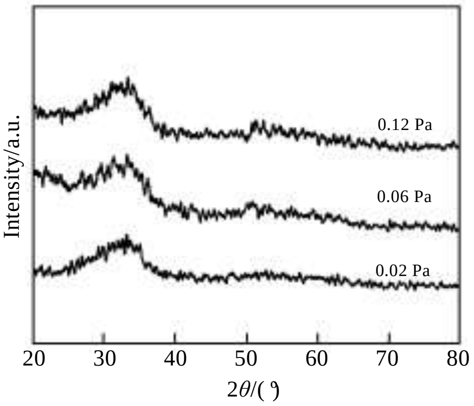

Fig.2 XRD patterns of IGZO films deposited under different sputtering pressures

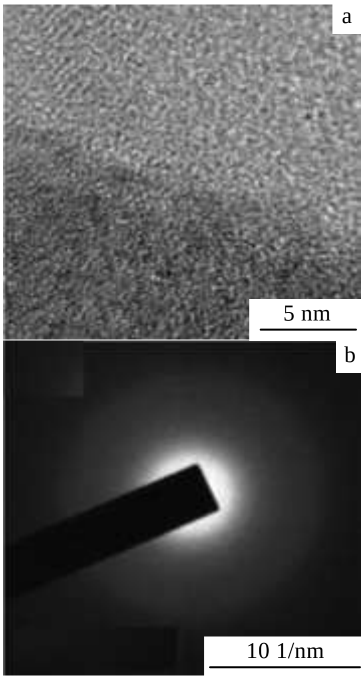

Fig.3 Bright-field TEM image of IGZO film deposited under 0.06 Pa (a) and the selected area electron diffraction pattern (b)

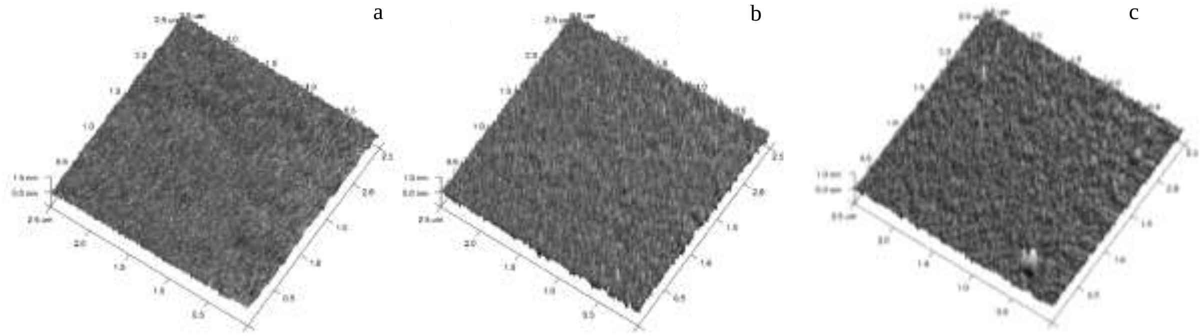

Fig.4 AFM images of a-IGZO films deposited under different sputtering pressures: (a) 0.02 Pa (RMS=0.114 nm), (b) 0.06 Pa (RMS = 0.148 nm), and (c) 0.12 Pa (RMS = 0.171 nm)

is enhanced, and consequently a large number of target atoms ejected will improve the scattering of the sputtered species, reducing kinetic energy of the incident ions. Hence, the mobility of the ions on the substrate surface is suppressed at higher pressure.

2.2 O 1s XPS spectrum of the IGZO thin film

XPS is used to analyze the chemical structure of the a-IGZO thin films. Fig.5 presents the O 1s peak of XPS spectra with different sputtering pressures, which can be fitted into two sub-peaks by Gauss fitting. The sub-peak I at lower binding energy is related to oxygen in metal oxide lattices and the sub-peak II at higher binding energy is assigned to the oxygen vacancies[8,13]. The relative area of the oxygen vacancy related sub-peak II decreases with increasing sputtering pressure, and they are 39.02%, 31.73%, and 12.53% for the case with sputtering pressures of 0.02, 0.06, and 0.12 Pa, respectively. The increasing sputtering pressure is attributed to the reduction of oxygen vacancies, where the oxygen vacancies of the film are compensated by O_2.

2.3 Hall Effect measurement of the IGZO thin film

By the Hall Effect measurement of a-IGZO thin films, the electrical properties of the film are indicated in Fig.6. It shows that the carrier concentration and hall mobility (μ_{hall}) decrease with increasing sputtering pressures, and the electronic conductivity was also decreased. It is consistent with the XPS results.

2.4 Characteristics of the a-IGZO TFTs

Fig.7 shows the characteristics of the a-IGZO TFTs devices, i.e., log(I_{DS})-V_{GS} and $(I_{\text{DS}})^{1/2}$-V_{GS} curves with drain voltage (V_{DS}=10 V). The saturation mobility (μ_{sat}) and the threshold voltage (V_{TH}) are derived from the slope and the intercept of a liner fitting on the V_{GS} axis in Fig.7b using the equation:

$$I_D = \left(\frac{C_i \mu_{\text{sat}} W}{2L}\right)(V_{\text{GS}} - V_{\text{TH}})^2, \quad \text{for } V_{\text{DS}} \geqslant V_{\text{GS}} - V_{\text{TH}} \tag{1}$$

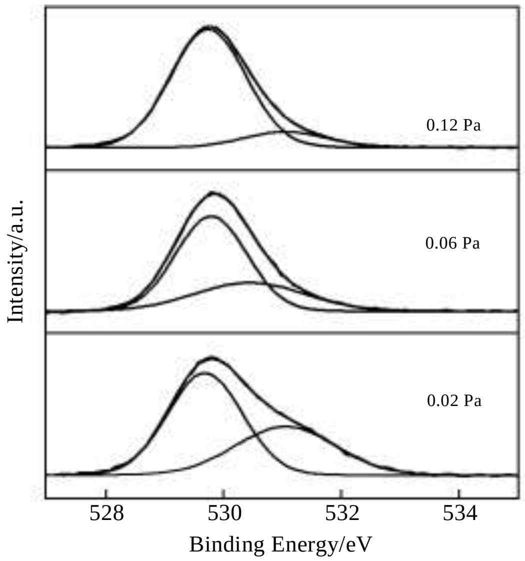

Fig.5 O 1s XPS spectra of IGZO films deposited under different sputtering pressures

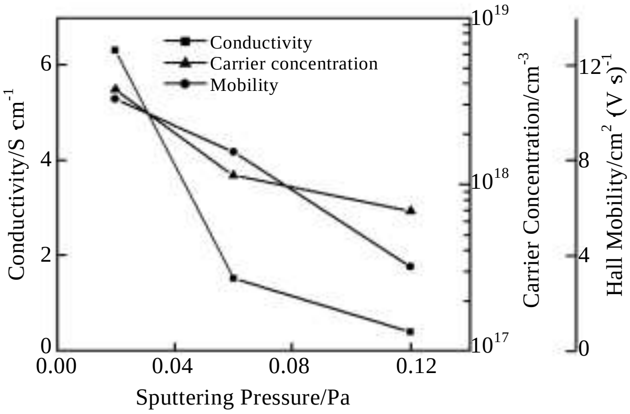

Fig.6 Electric properties of a-IGZO films deposited under different sputtering pressures

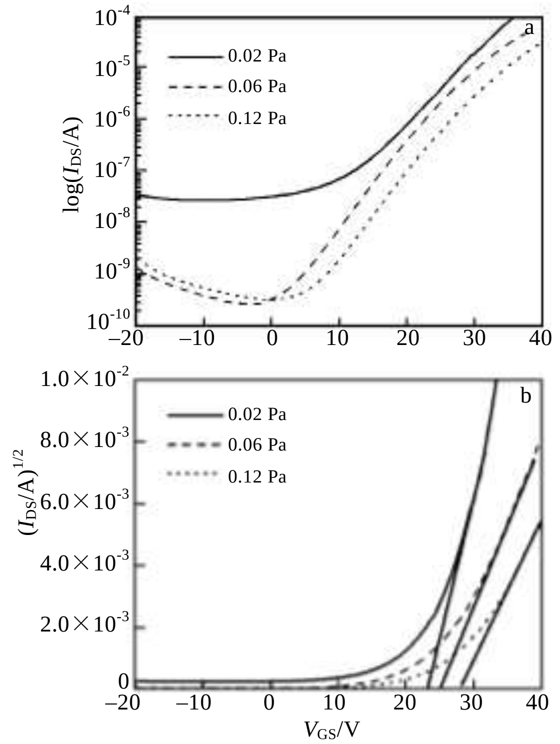

Fig.7 Transfer characteristics of a-IGZO TFTs with the channel layer deposited under different sputtering pressures: (a) log I_{DS}-V_{GS} and (b) $I_{DS}^{1/2}$-V_{GS}

where, W and L are the width and the length of the channel, respectively, C_i is the gate insulator capacitance per unit area, whose value is 34.5×10^{-9} nF/cm^2 in the sample of the work. It is noted that the V_{TH} increases and the saturation current decreases considerably with sputtering pressures. As for a-IGZO TFT deposited under a sputtering pressure of 0.02 Pa, more oxygen vacancies and higher carrier concentration are involved so that the off-state current is high, ~2.7×10^{-8}A, and the parameter $I_{on/off}$ ratio is only 8×10^3. Ideal transistor behavior is obtained on the enhancement mode of the a-IGZO TFTs for the cases with sputtering pressure of 0.06 and 0.12 Pa. The device performances of the former case are better than those of the later. For instance, their saturation currents are 6.6×10^{-5} and 2.9×10^{-5}A, V_{TH} are 24.6 and 28.9 V, the electron saturation mobility are 3.32 and 2.73 cm^2/(V s), the $I_{on/off}$ ratio are 2.7×10^5 and 1.0×10^5.

In fact by analyzing XPS spectrum and the hall-effect test, the films deposited under lower sputtering pressure have more oxygen vacancies and larger carrier concentration than those under higher sputtering pressure. As well known, each ionized oxygen vacancy in the a-IGZO thin films contribute two electrons to the conduction band, which is mainly responsible for the conductive characteristics of a-IGZO film. So the film under the lower sputtering pressure has larger carrier concentration and excellent conductivity. This usually leads to increased saturation current and the off-state current. Moreover, the larger surface roughness promotes the scattering of carriers, acting as trap state in the channel, and thus deteriorates the performance of the devices. In a word, the sputtering pressure plays an important role in the electrical properties of a-IGZO films and further influences the performance of the devices.

3 Conclusions

1) The electrical characteristics of a-IGZO TFTs are investigated on channel layer grown under different sputtering pressures but the same O_2 partial pressure. With increasing the sputtering pressure, the drain conductance decreases and the V_{TH} increases considerably.

2) The performance of the device with the channel layer deposited under the sputtering pressure of 0.6 Pa is the best; the μ_{sat} and V_{TH} are 3.32 cm^2/(V s) and 24.6 V, respectively.

3) The RMS values are 0.114, 0.148 and 0.171 nm for the thin films deposited under the sputtering pressure of 0.02, 0.06 and 0.12Pa, respectively. The smoother surface is obtained under reduced pressure.

4) The sputtering pressure affects the oxygen vacancies in the channel layer greatly, which is the source of the free carriers of a-IGZO film. The proper control of the sputtering pressures during the deposition plays an important role in achieving excellent performance for the fabricated a-IGZO TFTs.

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溅射压强对 a-IGZO 薄膜的表面粗糙度、氧空位及电学特性的影响

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摘 要：详细地研究了溅射压强对 a-IGZO 薄膜的微结构和电学特性产生的影响。AFM 分析表明，薄膜的表面粗糙度随溅射压强的增加而增大。XPS 分析表明薄膜中氧空位含量随溅射压强的增加而减少。增加表面粗糙度和减少氧空位对 a-IGZO 薄膜晶体管的特性有着决定性的作用。当溅射压强保持在 0.6 Pa 时，得到的薄膜晶体管的特性最佳，电子的饱和迁移率和门限电压分别是 3.32 $\mathrm{cm^2/(V\ s)}$ 和 24.6 V。溅射压强是磁控溅射制备 IGZO 薄膜及其晶体管的关键影响因素。

关键词：a-IGZO；薄膜晶体管；溅射压强；氧空位

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