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Research paper

Stability enhancement of low temperature thin-film transistors with atomic-layer-deposited ZnO:Al channels

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ABSTRACT

The electrical characteristics of TFTs with atomic-layer-deposited ZnO:Al (ZAO) channels have been studied in this work. By increasing Al doping concentration, the ZAO film changes from polycrystalline to amorphous, and its bandgap widens as well. With post-annealing at 200 °C, the superior electrical stabilities under illumination and gate bias stress were achieved in ZAO TFTs compared with ZnO TFTs. For the strong immunity to illumination in ZAO TFTs, it is attributed to the widening bandgap of channel material for the reduction of the carrier concentration. While for the improved electrical stability under positive bias stress, it is mainly due to the suppression of interactions between the amorphous channel and the surrounding ambient, which is verified by the observations in N_2 ambient.

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1. Introduction

Recently, transparent oxide semiconductors have attracted widespread interests because of high mobility, high transparency for visible light, and low process temperature [1–3]. In particular, the ZnO thin-film transistors (TFTs) using an oxide semiconductor as a channel layer have emerged for the next generation display application. However, the ZnO thin-film transistors (TFT) suffer from the instabilities under illumination and/or gate bias stress [4–6]. By doping with different chemical elements, the structural, optical, and electrical characteristics of ZnO films can be tuned properly. Ku et al. [7] reported that a small amount of Mg incorporated into the channel layer of ZnO TFTs by MOCVD at 400 °C exhibited a superior stability against negative stress bias. It was mainly attributed to the reduction of donor-like defects associated with ionized oxygen vacancies. Hafnium-doped zinc oxide (HZO) TFTs with post annealing at 400 °C have a smaller V_{th} shift of −1 V than that of −8 V for ZnO TFTs [8]. Furthermore, Cheremisin et al. observed that Indium-doped ZnO TFTs exhibit highly stable operational characteristics under both negative and positive bias stresses [9]. Obviously, such post-annealing steps underwent a relatively high thermal budget of 400 °C. However, in terms of flexible electronic applications, the maximum processing temperature of TFTs should be as low as possible meanwhile maintaining good performance. Therefore, it is also indispensable to explore the effect of low temperature annealing on the electrical characteristics of the ZnO TFTs.

In this work, the TFTs with Al-doped ZnO channels using atomic layer deposition were fabricated under the maximum thermal budget of 200 °C. The performance of ZnO TFTs with and without Al doping was compared quantitatively. Superior electrical stability under gate bias stress and illumination was achieved in the ZAO TFTs, and the mechanism behind was also analyzed.

2. Experimental details

A low resistive p-type (100) silicon substrate was used as the back gate of TFTs. After standard RCA cleaning, a 50-nm Al_2O_3 layer and ZAO active layer were deposited in turn by atomic layer deposition (ALD) at 200 °C without breaking vacuum. Herein, the precursors for ALD Al_2O_3 and ZnO films were $Al(CH_3)_3$ (TMA)/H_2O and $Zn(C_2H_5)_2$ (DEZ)/H_2O, respectively. The compositions of the ZAO films were modulated by the number of ZnO and Al_2O_3 deposition cycles. Here, n is the cycle ratio of the ZnO deposition cycles to the Al_2O_3 deposition cycles and thus the Al content increases as the cycle ratio decreases, as shown in Table 1. The elemental composition of Zn, Al and O in the ZAO films can also be roughly estimated from the cycle ratio, in agreement with the report [10]. Subsequently, the active layer of ZAO was defined by photolithography, and formed by wet etching with diluted HCl solution. Finally, the source/drain contacts of 100 nm Mo layer were formed by sputtering and a lift-off process. The schematic structure of the fabricated TFTs and process flow is illustrated in Fig. 1. After that, post-annealing at 200 °C in air for different annealing time was performed to improve the performance of the fabricated TFTs.

The thicknesses of the deposited ZAO and Al_2O_3 films were determined by an ellipsometer (Sopra GES-SE, France). The crystallinity and crystal orientation of deposited films were characterized by X-ray diffraction (XRD) with Cu KR radiation. The electrical characteristics of the TFTs with channel length/width (10 μm/100 μm) were measured

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Table 1
Compositions and thicknesses of ZnO and various ZAO films.

Sample	Cycle ratio (n)	Total cycles	Thickness (nm)	Al (at.%)	Zn (at.%)	O (at.%)
ZnO	N/A	200	41.2	0	50	50
ZAO-1	19:1	200	38.4	4.65	44.19	52.16
ZAO-2	9:1	200	37.1	8.70	39.13	52.17
ZAO-3	6:1	210	35.9	11.77	35.29	52.94
ZAO-4	4:1	200	32.4	15.38	30.77	53.85

with a semiconductor device analyzer (B1500A, Keysight Technologies) at room temperature in a dark box.

3. Results and discussion

With the additional Al_2O_3 growth cycles, the thickness of the ZAO film is observed to be thinner than that of the pure ZnO sample, shown in Table 1. Moreover, the thickness of ZAO film decreases with increasing Al doping concentration, which is attributed to the suppression of ZnO growth on Al_2O_3 [11]. Fig. 2 shows the XRD spectra of ZAO thin films with different Al concentration. It can be seen that ZAO exhibits a hexagonal wurtzite structure with the ZnO (100), ZnO (002), and ZnO (101) peaks. While with increasing Al contents, the diffraction angle shifts from 34.5° to 35.0°, indicating the substitution of Al^{3+} ions for Zn^{2+} ions in the ZnO lattice during the growth [12]. It is known that the ionic radius of Al^{3+} cation is 0.54 Å, which is smaller than that of Zn^{2+} cation (0.74 Å) [13]. The substitutional doping of Al^{3+} at the Zn^{2+} sites will lead to a reduction of the lattice parameter in the ZnO phase and consequently result in the peak shifting upward. In addition, it is also found that the intensity of diffraction peaks reduces gradually with increasing the amount of Al contents. As the deposition cycle ratio of ZnO:Al_2O_3 decreases to 6:1, the ZAO film (ZAO-3) becomes amorphous.

The optical properties of the ZAO films with different Al doping concentrations are also examined, as shown in Fig. 3. In the visible region, the transparency of the ZAO films increases with increasing Al doping concentration. For example, the transparency increased from 85.1% to 91.9% at a measured wavelength of 650 nm. Further, there is an obvious optical absorption for the ZnO film in the UV-light region in comparison with that of the ZAO film. According to Tauc's model the absorption reduces as their optical bandgap (E_g)

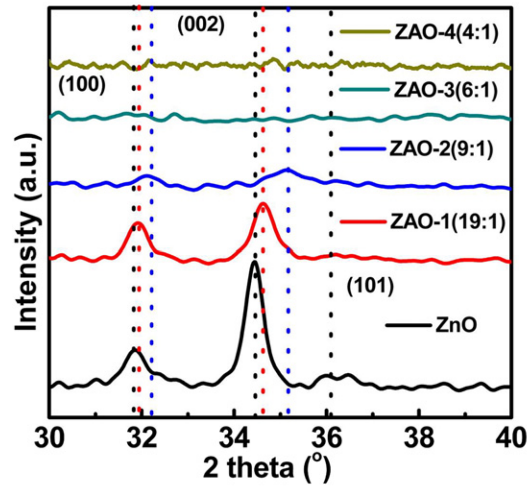

Fig. 2. XRD patterns for pure ZnO and ZAO thin films.

increases [14]. The optical bandgaps for the ZAO films with different Al doping concentrations were summarized in the inset table in Fig. 3. And it augments from 3.2 to 3.54 eV as the deposition cycle ratio of Al_2O_3: ZnO increases from 0 to 1:6.

Fig. 4 shows time-dependent transfer characteristics of TFTs with various channel compositions annealed at 200 °C in air. It is worthy noting that the as-fabricated TFTs behave like a resistor. Oxygen vacancies in ZnO could supply free electrons in the conduction band, and be passivated by the annealing in air, resulting in the reduction of carrier concentration in ZnO film. For the ZAO-1 TFT, it is known that ~5% Al incorporated into ZAO can act as an electron donor, contributing to an n-type conductivity of the ZnO films [15,16]. Such Al doped TFTs could maintain the high carrier concentration even it would decrease due to the passivation of oxygen vacancies by annealing in air. While for the ZAO-3 (Z:A = 6:1) TFTs, it was observed small on-current and on/off ratio due to the increase in the film resistivity. However, the ZAO-2 TFTs demonstrated a superior performance such as V_{th} of 0.8 V, on/off current ratio of ~10^7, field-effect mobility of 0.133 $cm^2/(V \cdot s)$ and subthreshold swing of 750 mV/dec, when the annealing time increased to 10 h. As a matter of fact, the ZAO-2 TFT exhibits a better performance than both ZAO-1 and ZAO-3 TFTs. The output characteristics of the

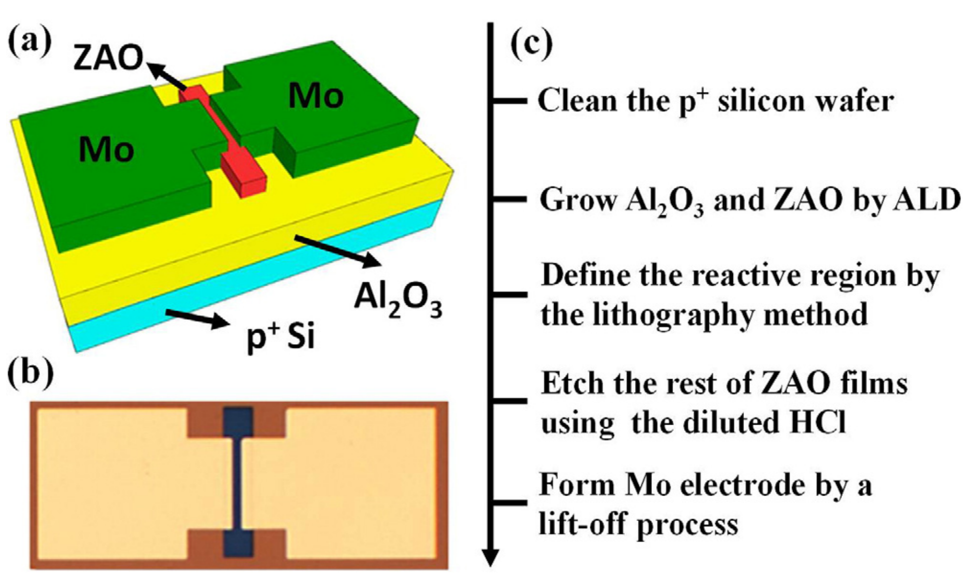

Fig. 1. (a) Schematic structure, (b) optical image and (c) process flow of the fabricated TFTs.

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