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Enhanced performance of indium zinc oxide thin film transistor by yttrium doping

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ABSTRACT

The Y^{3+}-doped indium zinc oxide thin film transistor devices were fabricated by the sol–gel spin-coating technique. The Y^{3+}-doped indium zinc oxide thin film transistor operates in n-channel enhancement mode and exhibits a well-defined pinch-off and saturation region. Because yttrium ion possesses lower electronegativity (1.22) and standard electrode potential (−2.372 V), it can act as the carrier suppressor to reduce the carrier concentrations of indium zinc oxide (In:Zn = 1:1) thin films from 1.29×10^{20} to 3.05×10^{14} cm^{-3} with the increase of Y^{3+} doping concentrations from 0 to 12 mol%. In addition, Y^{3+} (12 mol%)-doped indium zinc oxide thin film has the minimal surface roughness (1.067 nm) and lowest trap states (5.14×10^{12} cm^{-2}). Therefore, Y^{3+} (12 mol%)-doped indium zinc oxide thin film transistor possesses the optimum performance, and its field-effect mobility in the saturated regime, threshold voltage, on–off ratio, and S-factor are 4.76 cm^2/Vs, 4.3 V, 1.32×10^6, and 2.9 V/decade, respectively.

1. Introduction

Transparent oxide semiconductors (TOS) have received considerable attentions in the field of thin film transistor (TFT) devices because of their excellent optoelectrical properties such as high mobility, high transparency, low cost, robust, and low process temperature [1–11]. Many TOS-TFT systems such as indium oxide (In_2O_3) [1], zinc oxide (ZnO) [2–4], tin oxide (SnO_2) [5], indium-zinc oxide (In^{3+}-doped ZnO; IZO) [6–8], indium-gallium-zinc oxide (In^{3+}-Ga^{3+} codoped ZnO; IGZO) [9], and zinc-tin oxide (Zn^{2+}-doped SnO^2; ZTO) [10,11] have been studied in recent years. Generally, the doping of foreign ions can be used to improve the electrical properties (i.e., carrier concentration, mobility, and conductivity) of TOS thin films for the application of TFT devices.

It is known that the electronegativity and standard electrode potential (SEP) of foreign ions can influence their carrier-suppressed ability. The electronegativity and SEP of gallium are 1.81 and −0.52 V, respectively [12,13]. Hence, gallium acting as a carrier suppressor is the most popular to be doped in the IZO system [14,15]. On the other hand, Sc, Zr, or La can also be chosen to replace gallium as a carrier suppressor because of their low electronegativity and SEP value (the electronegativity values of Sc, Zr, and La are 1.36, 1.33, and 1.10 V, respectively [12], and the SEP values of Sc, Zr, and La, are −2.07, −1.45, and −2.379, respectively [13]).

In this paper, we chose yttrium as the carrier suppressor in the IZO system (In:Zn = 1:1) because of its lower electronegativity (1.22), SEP (−2.372 V), and cost. In addition, because In^{3+} and Y^{3+} ions have the same charge and similar ionic radius (In^{3+} = 0.0800 nm and Y^{3+} = 0.0891 nm), the addition of Y^{3+} ions to replace In^{3+} ions in the IZO structure cannot produce extra free charge carriers. The yttrium-indium-zinc oxide (YInZnO; YIZO) thin films were fabricated by the simple sol–gel spin-coating technique. Structural, optical, and electrical properties of the resulting YIZO thin films and inverted staggered-type YIZO TFT devices are systematically examined in terms of the structural evolution of the YIZO thin films at different yttrium doping concentrations.

2. Experiment

Anhydrous indium nitrate [$In(NO_3)_3$, 99.99%, Alfa Aesar] and zinc nitrate [$Zn(NO_3)_2$, 99.99%, Alfa Aesar] was added in the mixed solution of acetic acid (HAc, 99.5%, Acros) and 2-methoxyethanol (2-MOE, 99.5%, Merck) with the molar ratio of In/Zn/HAc/2-MOE = 1/1/20/12 to form the indium-zinc (In-Zn) solution. Yttrium nitrate [$Y(NO_3)\cdot 4H_2O$, 99.9%, Alfa] was then dissolved into the In-Zn solution to form the Y^{3+} (0, 6, 12, or 20 mol%)-doped indium-zinc (Y-In-Zn) precursor solutions, followed by stirring for 10 h in order to process homogeneous hydrolysis and polymerization reaction.

A simple bottom-gate and top-contact structure was adopted for TFT fabrication. Y-In-Zn precursor solutions were spin-coated on a highly doped p-type Si wafer (ρ = 0.001 Ω-cm) covered with a dry-oxygen thermally grown 100 nm thick SiO_2 layer as gate dielectric

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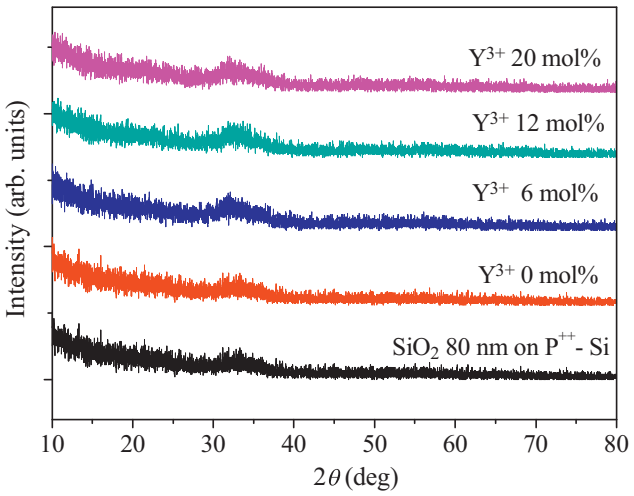

Fig. 1. GIXRD patterns of the YIZO thin films with 0, 6, 12, or 20 mol% Y^{3+} concentrations.

at a speed of 1500 rpm for 10 s followed by 4000 rpm for 30 s. The as-deposited sol–gel films were first dried at 100 °C for 10 min and pyrolyzed under dry air atmospheres at 500 °C for 60 min at a heating rate of 3 °C/min. An average film thickness measured from three samples with the same coating condition was 65 ± 5 nm. Then the YIZO film was patterned using lithography and wet etching process to eliminate the fringing effect. 100 nm-thick Al thin film was deposited on the patterned active layer through a shadow mask by thermal evaporation as source and drain electrodes. The channel width (W) and channel length (L) are 1000 μm and 100 μm, respectively (W/L = 10).

The grazing incidence X-ray diffraction (GIXRD) measurement of thin films was performed by an X-ray diffractometer (Bruker, D8 discovery) with CuKα radiation (λ = 0.154 nm), and X-ray incidence angle was fixed at 0.5°. The thickness of YIZO films was measured by the α-step profile meter (KLA-Tencor, Alpha-Step IQ). Transmission spectra in the UV and visible ranges were determined on a Thermo Scientific Evolution 220 spectrophotometer. X-ray photoelectron spectroscopy (XPS) was recorded by an AXIS Ultra DLD (Kratos) spectrometer equipped with Mg kα (1253.6 eV) radiation to investigate the chemical environment of elements. The background of XPS peak was subtracted with Shirely function, and the XPS signals of Y 3d and O 1s were fitted with mixed Gaussian curves. Binding energies were calibrated with respect to the C 1s peak at 285.0 eV. The conductivities, Hall mobility, and carrier concentration were measured at room temperature with the four-point van der Pauw method in a magnetic field of 0.55 T (ECOPiA, HMS-3000). The TFT electrical characteristics were measured in the dark at room temperature with an Agilent B2912A precision source/measure unit. The surface morphology and roughness of thin films were analyzed using atomic force microscopy (AFM) (SEIKO E-sweep System).

3. Results and discussions

3.1. Structural and optical properties

The GIXRD patterns in Fig. 1 show the effect of Y^{3+} concentrations on the phase evolution of YIZO thin films on SiO_2/Si wafer annealed at 500 °C for 1 h. A weak broad continuum around $2\theta = \sim 32°$ is the characteristic of amorphous structure for all samples. Obviously, there is no any Y_2O_3 phase even though the doping concentration of Y^{3+} ions is as large as 20 mol%. It implies that Y^{3+} ions homogeneously disturb in amorphous IZO structure, which avoids the segregation of excess Y^{3+} ions to form crystalline Y_2O_3 phase.

AFM images of the YIZO thin films with 0, 6, 12, and 20 mol% Y^{3+} ions on SiO_2/Si wafer annealed at 500 °C for 1 h are displayed in Fig. 2. The root-mean-square (rms) roughness of the films derived from AFM are 2.508, 1.504, 1.067, and 2.054 nm for the YIZO thin films with 0, 6, 12, and 20 mol% Y^{3+} ions, respectively. The Y^{3+} (12 mol%)-doped IZO thin film possesses the smallest rms roughness. The surface roughness plays a major role in the TFT device performance, and the active channel with the minimal surface roughness leads to the better TFT device performance [16–18].

Fig. 3(a) depicts of the effect of Y^{3+} concentrations on the optical transmittance spectra of YIZO thin films on glass (Corning, Eagle 2000) annealed at 500 °C for 1 h. The average transmittance calculated in the wavelength ranging 200–1000 nm of the YIZO thin films with 0, 6, 12, or 20 mol% Y^{3+} ions are 74.54, 76.08, 78.74, and 78.05%, respectively. It is interesting to note that for YIZO thin films Fig. 3(a) clearly shows the red-shift in the fundamental absorption edge with the increase of Y^{3+} concentrations.

The optical band gap (Eg) of the YIZO thin film which is a direct-transition-type semiconductor can be related to absorption coefficient (α) by

$$\alpha h\nu = \text{const}\ (h\nu - E_g)^{1/2} \quad (1)$$

Here we assume the absorption coefficient $\alpha = (1/d)\ \ln(1/T)$, where T is the transmittance and d is the film thickness. Fig. 3(b) plots the relationship of $(\alpha h\nu)^2$ versus photon energy (E) of the YIZO thin films with 0, 6, 12, or 20 mol% Y^{3+} ions, and the extrapolated optical band gaps of YIZO thin films are determined. The E_g of YIZO thin films increase from 3.1 to 3.48 eV with the increase of Y^{3+} concentrations from 0 to 20 mol %. Because the E_g of Y_2O_3 (5.8 eV) [19] is larger than that of In_2O_3 (a direct band gap of about 3.75 eV and an indirect band gap of about 2.62 eV) [20,21] and ZnO (3.37 eV) [22], the addition of Y^{3+} ions into the amorphous binary In_2O_3-ZnO system can result in the enlarged Eg of amorphous tertiary Y_2O_3-In_2O_3-ZnO system. Similar phenomena can also be observed in other systems such as LaIZO [23], ZrIZO [24], and ScIZO [25].

3.2. Electrical properties

The cross-sectional view of the TFT device structure used in the work is presented in Fig. 4 The channel width (W) to length (L) ratio used in the present study are 1000 and 100 μm, respectively (i.e., W/L was 10). The thickness of YIZO active layer is ~65 nm. Fig. 5(a) shows the transfer characteristics of the YIZO TFTs with 0, 6, 12, or 20 mol% Y^{3+} doping concentrations at a fixed drain voltage of 30 V. Obviously, only the sample with 12 mol% Y^{3+} doping concentration exhibits $>10^6$ on/off ratio. The output curves of the optimal YIZO TFT with 12 mol% Y^{3+} doping concentration are shown in Fig. 5(b). The TFT operates in n-channel enhancement mode and exhibits a well-defined pinch-off and saturation region.

The threshold voltage and field-effect mobility in the saturated regime are estimated using the following relation:

$$I_{DS} = \left(\frac{C_i \mu_{FE} W}{2L}\right)(V_{GS} - V_{TH})^2 for V_{DS} > V_{GS} - V_{TH} \quad (2)$$

where C_i is the capacitance per unit area of the gate dielectric, V_{TH} is the threshold voltage, and μ_{FE} is the field-effect mobility. The threshold voltage and the field effect mobility were computed from the x-axis intercept of the square root of I_D versus V_{GS} plot and the slope of the plot.

The gate-voltage swing, S, defined as the voltage required to increase the drain current by a factor of 10, is given by

$$S = \frac{dV_{GS}}{d(\log\ I_{DS})} \quad (3)$$