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Improved stability of aluminum co-sputtered indium zinc oxide thin-film transistor

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ABSTRACT[1]

The electrical performance and bias stability of radio-frequency magnetron co-sputtered aluminum-indium-zinc oxide (Al-IZO) thin-film transistors (TFTs) were investigated, with respect to the atomic proportions of Al. Other parameters such as the indium-zinc oxide (IZO) target power, oxygen partial pressure, and initial and process pressures of the chamber were fixed. At a low Al atomic ratio (0.62 wt.%), the electrical performance and bias stability of the Al-IZO TFT were optimized because of the suppression of the generation of oxygen vacancies and the strong bond between Al and oxygen atoms (Al–O; 501.9 kJ/mol). Compared to pure IZO TFTs, the Al-IZO TFT exhibited a small shift in the threshold voltage under bias stress conditions. A higher threshold voltage of −2.24 V and an improved subthreshold swing of 1.35 V/dec were also observed. We demonstrated that the Al-IZO TFT could be a promising candidate for switching and driving operations in mass-produced display applications.

1. Introduction

Amorphous-oxide semiconductor (AOS) thin-film transistors (TFTs) have attracted considerable attention because of their excellent electrical performances compared to conventional amorphous-silicon-based TFTs (a-Si TFTs), such as high electron mobility, low process temperature, wide area of application, and transparency in visible light. Thus, they can be used for applications in display devices such as active-matrix liquid-crystal displays (AMLCDs) and active-matrix organic light-emitting diodes (AMOLEDs) [1]. Among all AOSs, amorphous indium-gallium-zinc oxide (a-IGZO) is the most commonly used material in TFTs because of its high mobility of over 15 $cm^2 V^{-1} s^{-1}$ and good carrier-concentration controllability [2–4]. The Ga in a-IGZO can improve the stability of the TFTs by suppressing the generation of oxygen vacancies, which is considered the main cause of instability in TFTs under gate-bias stress conditions [5,6]. However, Ga is an expensive element because of its very low component ratio on earth. One of the problems currently faced by the semiconductor industry is the replacement of expensive and rare elements such as In and Ga in its products, which will help reduce the cost of production and achieve sustainable production. To resolve this problem, several researches have been conducted to find substitutes for these rare elements [7–9].

The instability of AOS TFTs is one of the main issues that must be resolved to enable mass production. Usually, the long-term stability of AOS TFTs can be effectively improved through the control of the various processing methods such as thermal annealing [10], passivation [11], and plasma treatment [12]. In addition, by incorporating a metal element that has a higher oxygen bonding energy in the active layer, the stability can also be improved [8–10]. Thus, recently, much effort has been put into the search for substitute elements with good stability. Among them, Al can be used as an alternative new element. Although it has higher oxygen bonding energy than Ga (Ga–O; 374 kJ/mol), and is abundant on earth (resulting in low cost), there is almost no report on aluminum-indium-zinc oxide (Al-IZO) TFTs so far [13,14]. In this paper, we focus on the improvement of the stability of AOS TFTs by incorporating a metal element that has a higher oxygen

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[1] AOS: Amorphous-oxide semiconductor; TFT: Thin-film transistor; a-Si TFT: Amorphous-silicon-based TFT; AMLCD: Active-matrix liquid-crystal display; AMOLED: Active-matrix organic light-emitting diode; a-IGZO: Amorphous indium-gallium-zinc oxide; IZO: Indium-zinc oxide; Al-IZO: Aluminum-indium-zinc oxide; GDS: Glow discharge spectrometer; XRD: X-ray diffraction; XPS: X-ray photoelectron spectrometer; PBS: Positive bias stress; NBS: Negative bias stress; UV–vis: Ultraviolet-spectrophotometer.

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bonding energy in the active layer. Therefore, we fabricated AOS TFTs using Al-IZO thin films with different Al composition ratios as the active-channel layer. It was found that the Al-IZO active layer with a low Al ratio exhibits improved characteristics and bias stability than other devices; unexpected structural and electrical performances were also observed, and these were analyzed.

2. Experimental details

Bottom-gate-type Al-IZO TFTs were fabricated using an n-type Si substrate heavily doped with As and covered by thermally oxidized SiO_2 (with 150 nm thick). The SiO_2 layer was used as the gate dielectric and the n-type Si substrate was used as the gate electrode. Firstly, in order to prepare thin-films with good adhesion, the Si substrates were cleaned in an ultrasonic bath with trichloroethylene, acetone, methyl alcohol, and deionized water for 10 min each, and then dried using an N_2 gas blower. And then, 20-nm amorphous Al-IZO thin films were deposited on the substrate at room temperature using Al_2O_3 (with a purity of 99.99%) and indium-zinc oxide (IZO, In_2O_3: ZnO = 90 wt.%: 10 wt.%) targets by RF magnetron co-sputtering. The Al_2O_3 target powers were changed (0, 10, 20, 30 W) to find the best composition ratio for Al. The other parameters were fixed as follows: the IZO target power was 50 W, the oxygen partial pressure for $[O_2/(Ar + O_2)]$ was set at 13%, the initial pressure of the chamber was 4×10^{-4} Pa, and the process pressure was 0.267 Pa. The channel area was formed using a shadow mask during the deposition process. Next, 100-nm-thick Al was deposited using a shadow mask by an e-beam evaporator to serve as the source/drain (S/D) electrodes. The fabricated TFTs had a channel width (W) and length (L) of 1000 μm and 100 μm, respectively. Finally, the fabricated Al-IZO TFTs were annealed at 250 °C for 1 h in air. Fig. 1 shows the cross-sectional schematic diagram of the fabricated bottom-gate-type Al-IZO TFTs.

3. Results and discussion

To investigate the composition ratios of Al in the deposited Al-IZO thin films for various Al_2O_3 target powers, a glow discharge spectrometer (GDS, HORIBA and JY 10000RF) was used. The samples deposited at a fixed oxygen partial pressure of 13% were annealed at 250 °C for 1 h in air. Table 1 shows the weight percentage of the In, Zn, and Al elements in Al-IZO thin film for different power of Al_2O_3 target. Consequently, the Al ratio was gradually increased with increasing Al_2O_3 target's power. In accordance with these results, we could control the Al_2O_3 target power to incorporate the best composition of Al into the IZO thin films.

Fig. 2 depicts the X-ray diffraction (XRD, PHILIPS and X' pert-MPD system) spectra of the fabricated samples used to analyze the crystallinity of the thin films. Samples were deposited on quartz glass, and annealed at 250 °C for 1 h. All thin films clearly indicated amorphous states without significant diffraction peaks, irrespective of the different Al_2O_3 target powers. These results suggest that Al-IZO thin films are promising candidates for the active layer in many electronic devices, owing to their advantages such as low temperature process and good uniformity in large-area applications.

Table 1
Weight percentages of the In, Zn, and Al elements in Al-IZO thin films for different powers of Al_2O_3 target.

Al_2O_3 Power [W]	In [wt.%]	Zn [wt.%]	Al [wt.%]
0	90.02	9.98	0
10	90.06	9.32	0.62
20	90.13	8.70	1.17
30	90.00	8.50	1.50

We analyzed the angle-resolved X-ray photoelectron spectroscopy (XPS, THERMO VG SCIENTIFIC and MultiLab2000) spectra to obtain the electrical properties from the chemical bonding states in the active-channel layers of the pure IZO and Al-IZO (Al_2O_3 power = 10 W) TFTs. All the samples were deposited on a Si substrate at a fixed oxygen partial pressure of 13%. As shown in Fig. 3, the O 1s spectrum was deconvoluted into two different peaks (O_L and O_H) using Gaussian fitting along with a Tougaard-type base line. The low binding-energy peak (O_L) at 530.20 eV is related to the O^{2-} ions in the fully oxidized stoichiometric films, and indicates the presence of Al-In-Zn-O lattice structures [15]. The high binding-energy peak (O_H) at 531.70 eV is usually attributed to the O^{2-} ions in the oxygen-vacancy regions within the Al-IZO matrix. In other words, it indicates the relative amount of oxygen vacancies in the Al-IZO matrix [16]. In order to compare the chemical characteristics of pure IZO and Al-IZO TFTs, we calculated the peak area ratio of each sample. The area ratio of O_L over the total O_{1s} peak, i.e., $(O_L/O_L + O_H)$, was 77.40% for the pure IZO thin film, whereas that for the Al-IZO thin film was 78.05%. This result could be because the Al metal added into the IZO thin film was easily oxidized as Al has a much lower standard electrode potential ($E^o = -1.66$ V) than Zn (−0.76 V) or In (−0.34 V). The lower the E^o, the more easily the metal is oxidized [17]. Thus, the oxidized Al^{3+} easily induces ionic bonding in the IZO thin films, resulting in fully stoichiometric Al-In-Zn-O lattice structures. As for the O_H peak area ratio $(O_H/O_L + O_H)$, the Al-IZO thin film exhibits a lower area ratio of 21.95% than the IZO thin film (which exhibits a ratio of 22.50%). This result implies that Al can reduce the chances of creating the oxygen vacancies from which the majority of the carriers originate, because Al metal cations have basically higher bonding energies with oxygen (Al–O; 501.9 kJ/mol) than other metal cations such as In (470 kJ/mol) or Zn (385 kJ/mol) [18,19]. From these results, we can validate the strong oxygenation capacity and oxygen-bonding ability of the Al metal.

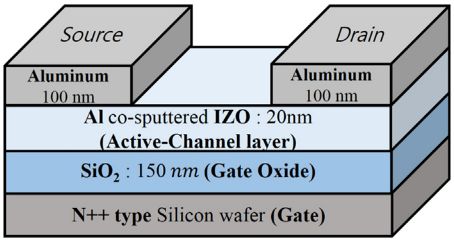

Fig. 1. Cross-sectional schematic diagram of the fabricated bottom-gate-type Al-IZO TFTs.

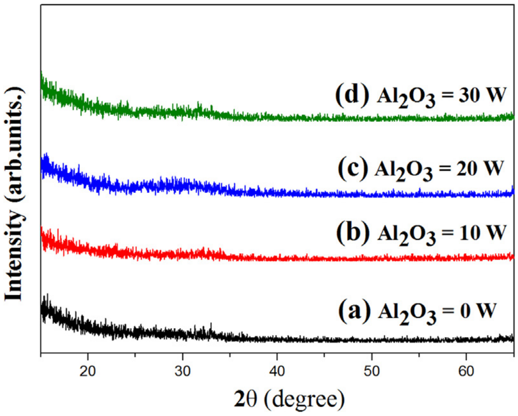

Fig. 2. XRD patterns of pure IZO and Al-IZO thin films for various Al_2O_3 target powers: Al_2O_3 power = (a) 0 W (b) 10 W (c) 20 W (d) 30 W.

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