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Effects of Mg doping on the gate bias and thermal stability of solution-processed InGaZnO thin-film transistors

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ABSTRACT

The effects of magnesium (Mg) doping (molar ratio Mg/Zn = (0–10 at.%)) on solution-processed amorphous InGaZnO (a-IGZO) thin-film transistors (TFTs) grown using the sol–gel method are investigated. TFT devices fabricated with Mg-doped films showed an improved field-effect mobility of 2.35 cm^2/V s and a subthreshold slope (S) of 0.42 V/dec compared to those of an undoped a-IGZO TFT (0.73 cm^2/V s and 0.74 V/dec, respectively), and an on–off current ratio of over 10^6. Moreover, the 5 at.% Mg-doped TFT device showed improved gate bias and thermal stability due to fewer oxygen deficiencies, smaller carrier concentration, and less interface electron trapping in the a-IGZO films.

1. Introduction

Amorphous InGaZnO (a-IGZO) thin-film transistors (TFTs) are attractive for use in active-matrix organic light-emitting diode displays (AMOLED) due to their superior performance, including high charge carrier mobility and high optical transparency [1,2]. However, sensitivity to the atmosphere is an extremely critical issue for a-IGZO TFT applications. The electrical properties and stability of oxide TFTs are strongly influenced by the oxygen content in both the bulk IGZO and the surrounding environment [3]. The environment-dependent instability has been attributed to oxygen adsorption/desorption reactions on the backchannel of an a-IGZO TFT device, which can be characterized under various biases, temperatures, and light illuminations [4–6]. Some studies have attempted to improve the TFT characteristics. Liu et al. reported that nitrogenating a-IGZO TFTs improved their gate bias stability by reducing the oxygen absorption/desorption reaction to the atmosphere [7]. Tsao et al. reported a hydrogen-induced improvement in a-IGZO-TFTs due to a reduced number of oxygen deficiencies [8]. Mg has been incorporated into IGZO because its standard electrode potential ($E = -2.37$ V) is much lower than those of Zn (−0.76 V) and In (−0.34 V), and its band gap ($E_g = 7.9$ eV) is higher compared to those of ZnO (3.3 eV) and In_2O_3 (3.6 eV). However, few researchers have focus on the effect of Mg doping on oxide TFTs. The sol–gel method with spin-coating was used in the present study to deposit IGZO films because it allows the physical and chemical properties of IGZO films to be easily controlled, making the films suitable for the active channel layer of TFTs [9–11]. The effect of Mg doping incorporated into the IGZO thin-film on the reduced oxygen deficiency and carrier concentration was studied. It has been found that IGZO-TFTs have native oxygen vacancies in the TFT channel, which can be thermally excited to the ionized state (V_O^{2+}) and lead to device instability [6,12]. To date, rare work discussed the thermal stability at high operational temperature. Hence, in order to determine the mechanism of oxygen vacancy related to the thermal stability of the TFTs, the device was measured from room temperatures to 200 °C. The gate bias-stress was also investigated.

2. Experimental procedure

2.1. IGZO films synthesized via the sol–gel method

IGZO films were prepared using the sol–gel technique. Zinc acetate dehydrate ($Zn(CH_3COO)_2{\cdot}2H_2O$, 99+%, Aldrich), indium nitrate hydrate ($In(NO_3)_3{\cdot}H_2O$, 99.9%, Aldrich), and gallium nitrate hydrate ($Ga(NO_3)_3{\cdot}H_2O$, 99.9%, Aldrich) were used as the precursors in 2-methoxyethanol (99.8%, anhydrous, Aldrich). Zn atoms were substituted by Mg atoms using magnesium acetate hydrate (($Mg(CH_3COO)_2{\cdot}H_2O$, 99.9%, Aldrich) (molar ratio Mg/Zn = (0–10%)). The concentration of metal precursors was 0.3 M and the molar ratio was 0.05:0.63:0.32 for Ga:In:Zn. Monoethanolamine (MEA 0.3M) was added as a sol stabilizer. A liquid film was deposited by spin-coating (SWIENCO/PM490) at a rotation speed of 3000 rpm for 30 s. The liquid film was dried at 200 °C on a hot plate for 10 min to evaporate organic compounds. The dried film was then annealed in a tube furnace at 400 °C for 30 min. The whole procedure was then repeated. The thickness was about 60 nm, as measured by an Alpha-Step profiler (AS500, KLA-Tencor). High-resolution X-ray photoelectron spec-

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troscopy (XPS) measurements were performed using a Kratos Axis Ultra DLD with a monochromatic Al Kα (1486.6 eV) source to analyze the types of chemical bonds of IGZO films.

2.2. Fabrication of IGZO TFTs

The bottom-gate TFT test structures were fabricated by spin-coating an a-IGZO semiconductor film onto a thermally grown 300-nm-thick gate dielectric layer of SiO_2. Additionally, the bottom electrode (In layer) was deposited on the top of heavily doped p-type Si substrates (resistivity of 0.001–0.005 Ω cm) as the gate to help the probing of the current flow from the gate to the substrate. On top of the TFT structure, 160-nm-thick Al layers were thermally evaporated via a shadow mask onto a-IGZO films as the source and the drain to complete the device coplanar stacks, as shown in the inset of Fig. 3. The dimensions of the TFTs were 200 μm (W) × 100 μm (L). All TFTs were characterized at room temperature in the dark under atmospheric conditions using a semiconductor parameter analyzer (4155C, Agilent).

3. Results and discussion

3.1. Characterization of Mg-doped IGZO films

A SEM image of the 5% Mg-doped IGZO film was shown in Fig. 1a. An amorphous phase with no prominent crystalline phase can be observed. The X-ray diffraction patterns of the undoped and Mg-doped a-IGZO thin films were obtained by using an X-ray diffractometer (Rigaku MiniFlex II) with Cu Kα radiation (λ = 0.154 nm) as shown in the inset of Fig. 1a. The undoped IGZO and Mg-doped a-IGZO films were also observed an amorphous phase with no prominent peak.

The Mg-doped IGZO films were deposited on a glass substrate (Corning 1737). A baseline measurement of the original substrate transmittance was obtained using an ultraviolet–visible (UV–Vis) spectrophotometer (U-3310, Hitachi). The prepared films had high average transmittance values (over 90%) in the visible region, as shown in Fig. 2. The absorption edge shifted towards a shorter wavelength region when the Mg doping was increased from 5% to 10%. This reveals that the doped Mg influenced the band gap, E_g, of IGZO. E_g was estimated by calculating the absorption coefficient using $\alpha = (1/t)\ln[1/T]$, where t is the film thickness and T is the transmittance. The absorption coefficient of a direct-band-gap semiconductor near the band edge is given by [13,14]:

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

where $h\nu$ is the photon energy and D is a constant. E_g can be extrapolated by plotting $(\alpha)^2$ vs E_g, as shown in the inset of Fig. 1b. Mg doping increased the E_g value from 3.67 (undoped IGZO) to 3.72 eV (10 at.% Mg-doped film). This observed blue shift can be explained by decreased oxygen vacancies. Excess oxygen vacancies act as shallow donors and supply conduction electrons, resulting in a narrower band gap [15,16]. This broadening of the band gap leads

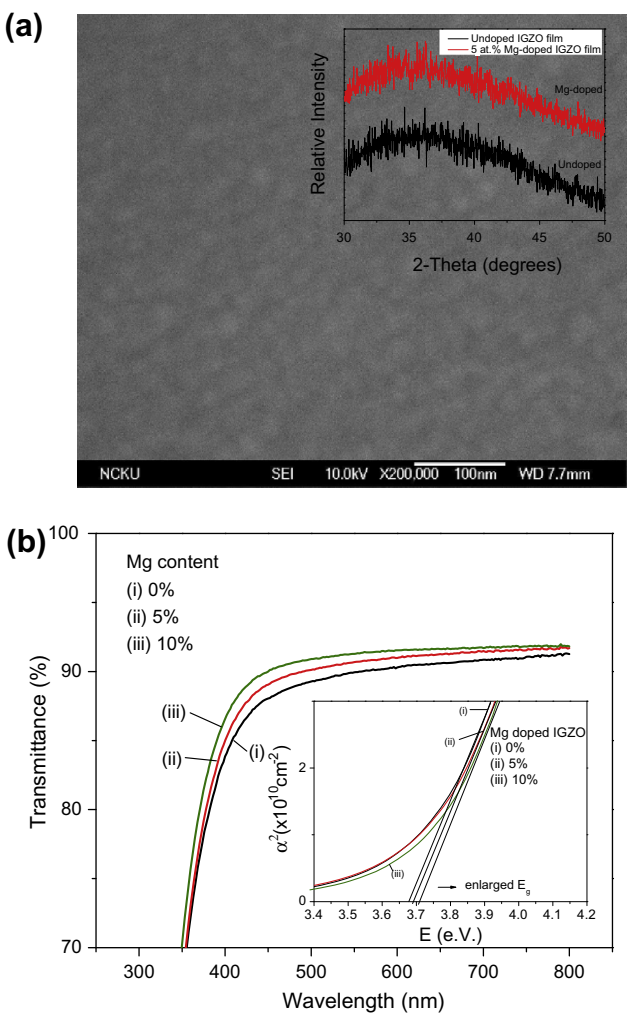

Fig. 1. (a) SEM image of the 5% Mg-doped IGZO film (Inset: XRD patterns of undoped a-IGZO and 5 at.% Mg-doped a-IGZO films.) and (b) transmittance spectra of as-deposited a-IGZO films prepared with various Mg dopant concentrations. (Inset: extrapolated E_g values for Mg-doped IGZO films.)

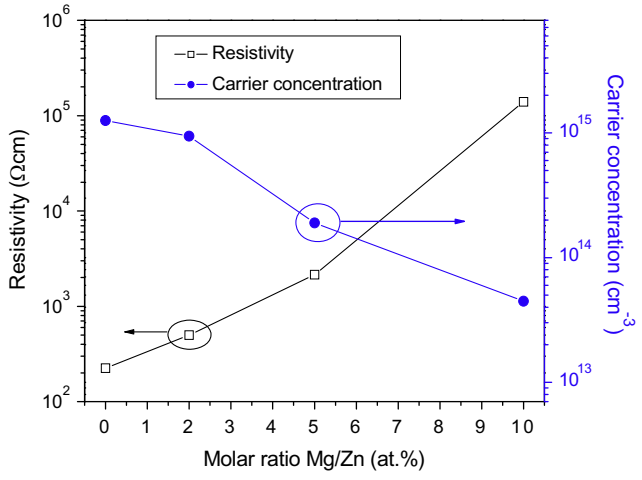

Fig. 2. Hall measurements of a-IGZO with various Mg dopant concentrations.

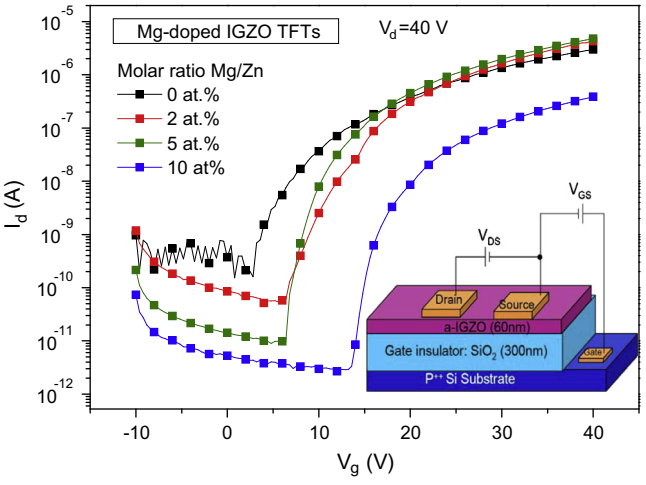

Fig. 3. Transfer characteristics (V_g vs I_d) of TFTs based on a-IGZO with various Mg dopant concentrations at V_d = 40 V.