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Effects of top-layer thickness on electrical performance and stability in VZTO/ZTO bi-layer thin-film transistors

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ABSTRACT

We examined vanadium-incorporated zinc tin oxide (VZTO) thin film transistors (TFTs) with various V contents and found that VZTO films easily become semi-insulators, even at small V contents (≥1.7 at%). We also fabricated VZTO/ZTO bi-layer TFTs with various VZTO top-layer thicknesses and investigated their electrical performance and stability. Regardless of the VZTO top-layer thickness, the VZTO/ZTO TFTs exhibited the transfer characteristics of a typical TFT because VZTO top-layers had semiconducting properties, unlike single VZTO films. As compared to the reference ZTO TFT, the stability of all the bi-layer TFTs under bias and/or illumination stress was significantly improved.

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1. Introduction

There has been a great upsurge of interest in the application of amorphous oxide semiconductors such as InZnO (IZO), ZnSnO (ZTO), HfInZnO (HIZO), InZnSnO (IZTO) and InGaZnO (IGZO) for the channel-layers of thin film transistors (TFTs) in display technology [1–5]. This is due to their excellent advantages such as high mobility, good uniformity, low-temperature processability, and good transparency. However, for the application of oxide TFTs into practical displays, the stability of oxide TFTs under various stress conditions such as bias, temperature, illumination, and their combinations must be guaranteed. The efforts of significant previous studies have established the following basis for these semiconductors. First, the subgap density of states (DOS) of an oxide semiconductor determines the basic operation and stability of the oxide TFT [6–8]. Second, in many cases (oxygen-deficient process conditions such as low oxygen partial pressure, vacuum-annealing, etc.), oxygen vacancies are treated as the entity that occupies most of the subgap DOS (deep-gap states), with the exception of tail states that originate from fluctuations of metal–oxygen bond lengths and angles [8]. Third, an oxygen vacancy ($\mathbb{V}_O$) can be ionized by thermal energy or photons to eject carrier electrons into the channel-layer and to occupy a higher energy level [9,10]. Finally, the suppression of $\mathbb{V}_O$ in the channel-layer is thus an effective method for enhancing the stability of oxide TFTs [11–16]. Based on this common knowledge, some elements such as Hf [11,12], Ti [12], Ga [12,13], and Zr [12,14] have been chosen as $\mathbb{V}_O$ suppressors and incorporated into host materials. However, the incorporation of $\mathbb{V}_O$ suppressors results in severe degradation of mobility because the $\mathbb{V}_O$ also acts as a carrier electron donor through its ionization, and the mobility of an oxide semiconductor generally increases with increasing carrier concentration [7,17]. Therefore, bi-layer structures such as HIZO/IZO [18], HfZnO/ZnO [19], ZTO/IZO [20], AlZnO/ZnO [21], Hf-incorporated ZTO (HZTO)/ZTO [22] and V-incorporated ZTO (VZTO)/ZTO [23] have been devised as trade-off structures. These structures consist of a bottom-layer for high mobility and a top-layer for high stability in the bottom-gate structure. Among many interesting results on bi-layer structures [18–23], we reported the unusual electrical behavior of VZTO films [23]. We found that although the single VZTO film behaved like a semi-insulator, the VZTO film on the ZTO bottom-layer exhibited a semiconducting property, and as a result the VZTO/ZTO bi-layer TFT exhibited good TFT characteristics. The semi-insulating behavior of the single VZTO film was attributed to the reduction of both $\mathbb{V}_O$ and

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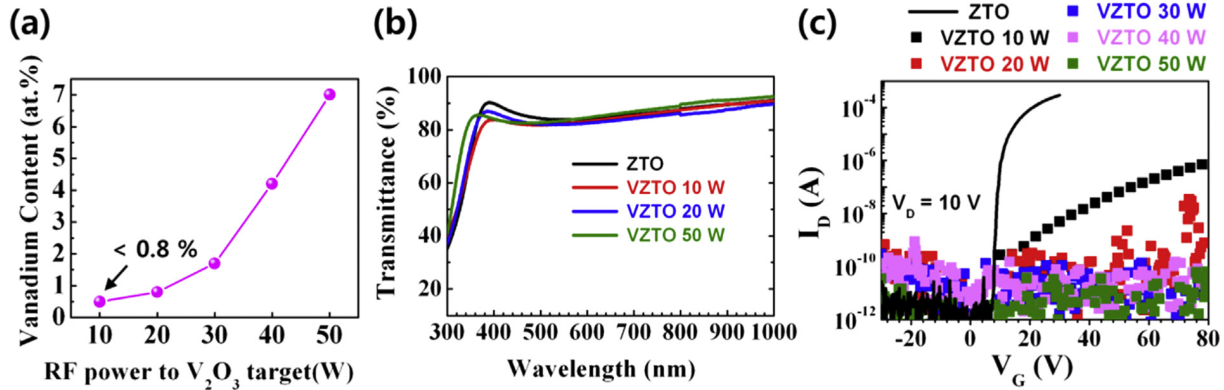

Fig. 1. (a) EDS results of VZTO films with various RF powers applied to the V_2O_3 target: 10, 20, 30, 40, and 50 W. (b) Optical transmission spectra of VZTO films with various RF powers applied to the V_2O_3 target: 10, 20, and 50 W. (c) Transfer characteristics of VZTO TFTs, as compared to the ZTO TFT.

multivalent metal atoms with high oxidation states (Sn^{4+} to Sn^{2+}, V^{5+} to V^{4+}). In contrast, the semiconducting VZTO film on ZTO resulted from the predominance of high oxidation states in multivalent metal atoms (Sn^{4+} and V^{5+}). Finally, we discovered that the VZTO/ZTO bi-layer TFT could provide good electrical performance and excellent photo-bias stability. However, we did not investigate the dependence of electrical performance and stability on the VZTO top-layer thickness as well as VZTO. In fact, the top-layer thickness may be one of the most important factors in the optimization of bi-layer TFTs. It has been known to determine electrical performance according to previous research based on a DOS-based device simulation for bi-layer TFTs [18]. In this study, therefore, we fabricated VZTO/ZTO bi-layer TFTs with various top-layer (VZTO) thicknesses and investigated the dependence of the electrical performance and stability of VZTO/ZTO bi-layer TFTs on VZTO top-layer thickness.

2. Experimental

We fabricated inverted-staggered bottom-gate TFTs on heavily-doped p-type Si substrates (0.001 Ω·cm, ~1.7×10^{20} cm^{-3} boron-doped) with thermally-grown SiO_2 (200 nm) as a gate insulator. All channel-layers were deposited on the substrates at room temperature via radio-frequency (RF) magnetron sputtering. We used a ZTO target (4 in.) with a Zn:Sn atomic ratio of 4:1 for deposition of the 80-nm-thick ZTO layer. While depositing the 80-nm-thick VZTO layer, vanadium was incorporated via a co-sputtering method using both ZTO and V_2O_3 targets. The concentration of vanadium was controlled by the RF power applied to the V_2O_3 target. For the deposition of the VZTO/ZTO bi-layer, the VZTO film was in-situ co-sputtered on the pre-deposited ZTO film (80 nm). The thicknesses of the VZTO layers were adjusted simply through deposition time to be 20, 40, and 80 nm. The channel region was isolated via conventional photolithography and a wet etching process. All the isolated films were thermally annealed at 350 °C in N_2 gas for 3 h. The Ti/Au/Ti (10/80/10 nm) source and drain (S/D) electrodes were formed via electron beam evaporation at room temperature. Shadow masks were used to define the S/D electrodes, and the channel length (L) and width (W) were 50 and 500 μm, respectively. No passivation layers were deposited. Finally, all TFTs were thermally annealed at 250 °C in ambient air for 30 min. The thickness of the channel-layers was measured using a surface profilometer (XP-100, Ambios Technology, Inc.) according to the following procedure: i) patterning channel-layers on the substrates; ii) annealing the patterned channel-layers; and iii) measuring and averaging the thicknesses of 8 channel-layers among 16 channel patterns. Additionally, we double-checked the film thicknesses with a scanning electron microscope (SEM, JSM-6700F, JEOL Ltd.) as shown in Fig. S1 and found that the film thicknesses were well controlled. The transmittance of the ZTO and VZTO films on glass substrates (Eagle XG, Corning Inc.) was measured by an ultraviolet–visible–near infrared (UV–vis–NIR) spectrophotometer (Cary 5000, Varian Inc.). Energy-dispersive spectroscopy (EDS, JSM-6700F, JEOL Ltd.) was employed to verify the V:Zn:Sn composition ratios of the ZTO and VZTO. The ZTO, VZTO, and VZTO/ZTO films were characterized by grazing angle incident X-ray diffraction (GIXRD, D8 ADVANCE, Bruker Co.) to identify the relationship between the structural variation and electrical conductivity of the films. All current–voltage (I–V)

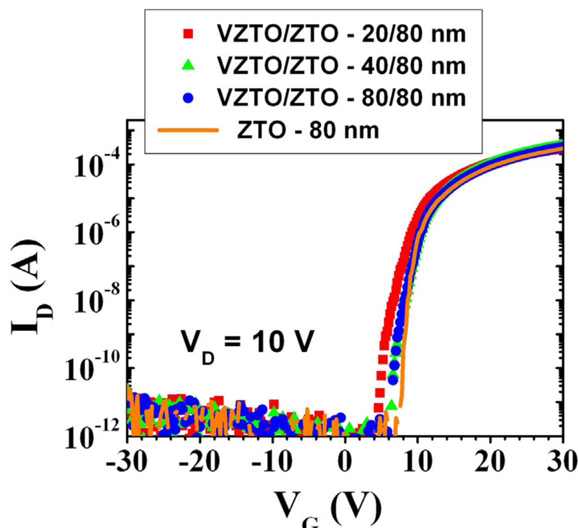

Fig. 2. Transfer characteristics of VZTO/ZTO bi-layer TFTs with various thicknesses of VZTO top-layer: 0, 20, 40, and 80 nm.

Table 1
Parameters extracted from GIXRD data and Scherrer's equation.

Structure	Peak position, 2θ [degree]	FWHM, β [degree]	Crystallite size [nm]
ZTO – 80 nm	34.3	4.1	2.03
VZTO – 80 nm	34.2	4.2	1.98
VZTO/ZTO – 40/80 nm	34.3	4.0	2.08
VZTO/ZTO – 80/80 nm	34.3	4.4	1.89

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