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The influence of oxygen partial pressure on the performance and stability of Ge-doped InGaO thin film transistors

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Abstract

The device performance and bias stability of radio frequency (RF) sputtered Ge-doped InGaO (GIGO) thin film transistors (TFTs) were investigated as a function of oxygen partial pressure during the deposition step. At low oxygen partial pressure, the electrical performance and stability of GIGO TFTs were significantly improved with a decrease of oxygen deficient bonding states, suggesting strong oxygen bonding ability of Ge atoms. We demonstrate that these changes can be corroborated with the evolution of the electronic structure, such as band alignment and band edge states below the conduction band, as measured by X-ray photoelectron spectroscopy and spectroscopic ellipsometry analysis. As the oxygen partial pressure decreased, the energy difference between the conduction band minimum and Fermi level and the deep band edge states was decreased. In particular, it was revealed that, with an increase of oxygen partial pressure, the relative energy level of the band edge states was shifted to a deeper level within the bandgap.
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Keywords: Oxide semiconductor; Thin film transistor; Ge–In–Ga–O; Oxygen pressure; Bias stability

1. Introduction

Amorphous oxide semiconductor-based thin film transistors (AOS-TFTs) have been extensively studied for applications in backplane electronic devices such as active-matrix liquid crystal displays (AMLCDs) and organic light-emitting diodes (AMOLEDs) due to their high field effect mobility, good gate swing, low temperature processing capability, and transparency to visible light [1–4]. Following Hosono et al.'s report on amorphous indium–gallium–zinc oxide TFTs with promising device performance, various oxide semiconductors based on indium, zinc, and tin oxide compounds have been intensively studied [3].

However, in terms of practical mass production, the fabrication of AOS-TFTs with higher device performance and better device stability remains the most important issue. Recently, a great deal of effort has been placed on searching for alternative oxide semiconductors with excellent stability under bias and illumination stress, mainly through the use of a combinatorial material design approach [5,6]. In addition, various oxide semiconductors have been investigated as a TFT channel layer to enhance the TFT characteristics by controlling the carrier concentration and mobility. Several research groups have also studied optimization of the device structure, materials, and process parameters in order to understand and thereupon address the degradation of device performance and stability [7–9]. While previous reports have suggested that the device operation and stress induced device instabilities are predominantly due to the charge trapping mechanism related to oxygen defects, the origins and interpretations of device instability remain unclear [10,11]. More detailed and systematic approaches in terms of elucidating the electronic structure of oxide semiconductors are thus necessary, because it may be strongly related to the charge transport and trapping behaviors, which influence the device characteristics.

In the present work, device performance and bias instability of Ge-doped InGaO (GIGO) oxide TFTs (where the role of Ge

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is to control the net electron carrier concentration by suppressing carrier generation via oxygen vacancy formation) are investigated as a function of RF-sputtered oxygen pressure, with respect to the electronic structure of band alignment and band edge states below the conduction band, which are also correlated to the chemical bonding states. It was found that a GIGO active layer deposited under lower oxygen partial pressure exhibits better device characteristics, with reduced oxygen deficient chemical bonding states and deep band edge states.

2. Experiment

A heavily doped p-type Si wafer with a thermally grown SiO_2 (100 nm) wafer was used as a substrate onto which GIGO films were deposited using a single ceramic target (with a composition of Ge_2O_3:In_2O_3:Ga_2O_3=1:7:2 mol%), without substrate heating, by a radio frequency (RF) sputtering system. The RF power and oxygen partial pressure [O_2/(O_2+Ar)] were set to 75 W and changed from 2% to 20%, respectively. The active area was defined using a shadow mask during GIGO film deposition. The indium–tin-oxide (ITO) source/drain (S/D) electrode was then deposited and patterned again using shadow masks. The fabricated TFTs had a bottom gate structure, and a channel width (*W*) and length (*L*) of 1000 μm and 150 μm, respectively. Finally, GIGO TFTs were annealed at 350 °C for 1 h, by using a furnace system. In order to analyze the physical and electronic properties of GIGO films, separated GIGO films were prepared on identical substrates and subjected to the same heat treatments as for the TFT devices. Regardless of the oxygen partial pressure, the film composition, investigated by Rutherford backscattering spectroscopy (RBS), was ~10% Ge doping into InGaO, and the physical structure, measured by X-ray diffraction (XRD), was preserved as an amorphous structure. Chemical bonding states were also examined by X-ray photoelectron spectroscopy (XPS), using a monochromatic AlKa source, with a pass energy of 20 eV. The electronic structures, which are related to changes in band alignment and band edge states below the conduction band, were investigated by XPS and spectroscopic ellipsometry (SE). The SE measurements were performed by a rotating analyzer system with an auto retarder in an energy range of 0.75–6.4 eV with incident angles of 65°, 70°, and 75°.

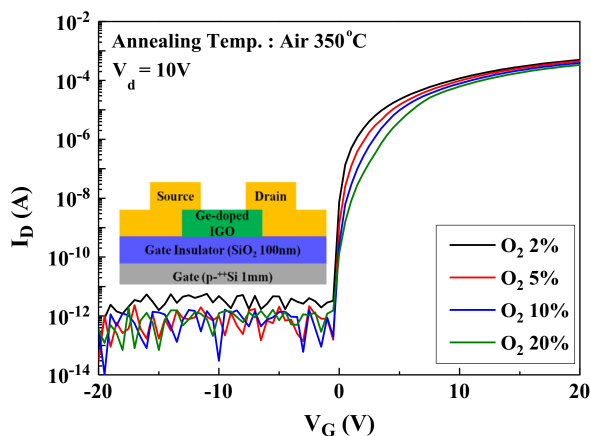

Fig. 1. Representative transfer characteristics of GIGO TFTs as a function of the oxygen partial pressure and schematic diagram of GIGO TFTs (inset).

3. Results and discussion

Fig. 1 shows the representative transfer characteristics of the TFTs with the GIGO active layer deposited under different oxygen partial pressures of 2%, 5%, 10%, and 20%. The field effect mobility (μ_{FE}) and threshold voltage (V_{th}) in the saturation region (V_{DS}=10.1 V) were calculated by fitting a straight line to the plot of the square root of I_{DS} vs. V_{GS}, according to the expression for a field-effect transistor [12]. The subthreshold gate swing (SS) value was extracted from the linear part of the log(I_{DS}) vs. V_{GS} plot [13]. A significant improvement of the device performance was observed for the TFTs with the GIGO active layer deposited under an oxygen partial process pressure of 2%, and the detailed device parameters are summarized in Table 1. As the oxygen partial pressure decreased from 20% to 2%, the μ_{FE} and SS values in GIGO TFTs significantly improved, from 11.33 cm^2/V s and 0.29 V/decade to 14.46 cm^2/V s and 0.12 V/decade, respectively. These results suggest that the oxygen partial pressure is a critical factor in controlling the charge-trapped defects in the GIGO semiconductor and/or interface (GIGO/SiO_2), due to improved mobility and SS values [14].

The RBS analysis revealed that the oxygen composition of the GIGO film slightly increased from 61.1% to 63.1%, as the oxygen partial pressure increased from 2% to 20%. However, the indium (In) element in GGIO films slightly decreased from 22.2% to 21.1% without altering other elements (Ga and Ge). Generally, it is quite reasonable to assume that higher oxygen partial pressure would lead to greater incorporation of oxygen element into the GIGO film. Thus, the compositional change of In and oxygen elements can affect the mobility and oxygen-related defects.

Fig. 2 depicts the crystallinity of the GIGO films after 350 °C annealing. All films have an amorphous structure independent of the oxygen partial pressures. This suggests

Table 1
Comparison of various device parameters of GIGO TFTs as a function of the oxygen partial pressure.

	V_{th} (V)	Mobility (cm^2/V s)	SS (V/decade)	On/off ratio	Hysteresis (V)
O_2 2%	1.50	14.46	0.12	2.47E+10	0.13
O_2 5%	1.97	13.93	0.13	3.09E+09	0.22
O_2 10%	2.40	12.59	0.21	1.32E+10	0.35
O_2 20%	2.60	11.33	0.29	8.44E+09	0.71

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