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Sputtered boron indium oxide thin-film transistors

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ABSTRACT

Boron indium oxide (BIO) is studied for thin-film transistor (TFT) channel layer applications. Sputtered BIO thin films exhibit an amorphous phase over a wide range of B_2O_3/In_2O_3 ratios and remain amorphous up to 500 °C. The band gap decreases linearly with decreasing boron content, whereas device performance generally improves with decreasing boron content. The best amorphous BIO TFT exhibits a field-effect mobility of 10 $cm^2 V^{-1} s^{-1}$, turn-on voltage of 2.5 V, and sub-threshold swing of 0.72 V/dec. Decreasing the boron content to 12.5% leads to a polycrystalline phase, but further increases the mobility up to 20–40 $cm^2 V^{-1} s^{-1}$. TCAD simulation results suggest that the reason for higher performance after increasing the anneal temperature from 200 to 400 °C is due to a lower defect density in the sub-bandgap region of the BIO channel layer.

1. Introduction

The flat-panel display industry is greatly interested in semiconductors with high mobility. This is driven by trends toward higher resolution, faster refresh rate active-matrix liquid-crystal displays (AMLCDs) as well as the emergence of active-matrix organic light-emitting diode (AMOLED) displays. These technologies have an increased requirement on the electron mobility compared to what the traditional hydrogenated amorphous silicon (a-Si:H) backplane material can provide. Recently, amorphous oxide semiconductors (AOSs) have attracted attention, and amorphous In-Ga-Zn-O (a-IGZO) specifically due to its relatively high electron mobility (~10 $cm^2 V^{-1} s^{-1}$) and compatibility with existing manufacturing methods for large-area glass substrates [1–3]. However, AOSs with even higher mobility than that of a-IGZO are desired for future active-matrix displays [4].

In this work, we study sputtered boron indium oxide (BIO) for use as channel layer in a thin-film transistor (TFT). Boron bonds to oxygen very strongly compared to other cations commonly used in the design of AOSs such as Al, Ga, or Zn. The bond strength for selected metal-oxides is summarized in Table 1. A high carrier concentration, which is undesirable for use as a channel layer, is usually attributed to oxygen vacancies in the AOS. Due to its high oxygen bond strength boron should work very well at reducing oxygen vacancies in the In-O system and, hence, act as a carrier suppressor. Gallium is commonly thought of as a carrier suppressor in a-IGZO, however, it also reduces the mobility [3]. Our hypothesis is that a smaller size cation will not greatly impact the electron transport among In-In s-orbitals. Boron is a very small element compared to Ga or any of the other relevant AOS cations, see atomic radii in Table 1. Potentially, this could lead to a high mobility of BIO. Boron oxide also has a large band gap of ~8 eV [5] which will aid in increasing the overall band gap of the boron-doped In-O system.

Kumomi et al. [6] report the fabrication of a TFT with a B-In-O channel layer as part of a large combinatorial study. However, no composition or device performance metrics are provided. Parthiban et al. [7] study boron-doped In-Zn-O (BIZO) and report devices with a field-effect mobility of 9.6 $cm^2 V^{-1} s^{-1}$. They did not vary the stoichiometry of their BIZO semiconductor.

We investigate BIO over a wide range of B_2O_3/In_2O_3 ratios from 12.5 to 50 mol% B_2O_3. First, the amorphous nature and band gap of BIO thin films are analyzed. Second, TFTs are fabricated for each BIO composition studied and the sputtering conditions are optimized. Finally, technology computer-aided design (TCAD) simulation is used to analyze the improved performance of amorphous BIO TFTs with higher anneal temperature.

2. Experimental details

High purity B_2O_3 and In_2O_3 powders were mechanically pressed and sintered in air to achieve dense sputtering targets with a 5 cm

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Table 1
Comparison of boron with commonly used cations in the design of an AOS.

Metal oxide	Bond dissociation energy (eV)	Atomic radii of cation (pm)	Band gap (eV)
B-O	8.4	86	8.0
Al-O	5.3	143	7.5
Ga-O	3.0	135	4.5
In-O	3.7	167	2.9
Sn-O	5.7	151	3.6
Zn-O	2.9	134	3.3

With data from J.A. Dean, Lange's Handbook of Chemistry 15th ed., McGraw-Hill (1998).

diameter. Ceramic targets were prepared with a fixed stoichiometry of 50/50, 25/75, 17.5/82.5, and 12.5/87.5 mol% B_2O_3/In_2O_3 from here on referred to as 50BIO, 25BIO, 17.5BIO, and 12.5BIO, respectively. Thin films were deposited via radio-frequency sputtering on fused silica substrates or SiO_2/Si substrates for scanning transmission electron microscopy (STEM). Sputtering was done at a pressure of 5 mTorr, an applied RF power density of 2.55 W cm^{-2}, and a process gas ratio of $O_2/(Ar + O_2) = 10\%$. Devices were fabricated on p-type Si substrates with an Au/Cr coated back side to act as the gate electrode. The gate insulator consists of 100 nm of thermal SiO_2. The BIO channel layer was sputtered using the same conditions as the thin films. Additionally, for device optimization the sputtering ambient was varied between $O_2/(Ar + O_2) = 0$ and 20%. No intentional heating was used during sputtering. A post-deposition anneal of 200–500 °C was performed in air. Source/drain contacts were formed using thermal evaporation of aluminum. The channel layer and source/drain contact areas were patterned via shadow mask. The final device had dimensions of width/length = 1000 μm/200 μm.

A Rigaku Ultima IV system with a grazing incidence angle of 0.35° was used for the X-ray diffraction measurement (GI-XRD). The optical absorption was analyzed using an Ocean Optics UV–Vis spectrometer. The STEM high-angle annular dark-field (HAADF) imaging and selective-area electron diffraction (SAED) was conducted using an FEI Titan 80-200 microscope. Devices were characterized at room temperature in the dark with an Agilent 4155C semiconductor parameter analyzer. Field-effect mobility (μ_{FE}) was extracted at a drain voltage of $V_{DS} = 0.1$ V and a gate voltage of $V_{GS} = V_{ON} + 30$ V. Turn-on voltage (V_{ON}) is defined as the voltage where the initial onset of drain current occurs, which is at approximately 10 pA.

3. Results and discussion

3.1. Thin film characterization

Fig. 1 shows that 50BIO, 25BIO, and 17.5BIO thin films remain amorphous even after an anneal at 500 °C, characterized by the broad peaks in the diffraction pattern. Further GI-XRD analysis shows that the 50BIO, 25BIO, and 17.5BIO thin films are amorphous up to 550, 525 and 515 °C, respectively. The trend of amorphous phase stability versus boron content is summarized in Fig. 4(a). Amorphous phase stability in Fig. 4(a) is defined as the maximum anneal temperature before crystallization occurs. The 12.5BIO thin film is polycrystalline as-deposited. The peaks in the GI-XRD pattern of the 12.5BIO thin film, as shown in Fig. 1, can be referenced to bixbyite In_2O_3. This suggests that the 12.5BIO sample phase segregates into polycrystalline In_2O_3 and amorphous B_2O_3. At this low boron composition, the B_2O_3 content in the BIO system is too small to sustain an amorphous phase. Overall, B_2O_3 seems to be quite effective as an amorphous phase stabilizer in the In-O system. This was not necessarily expected considering the small size of boron.

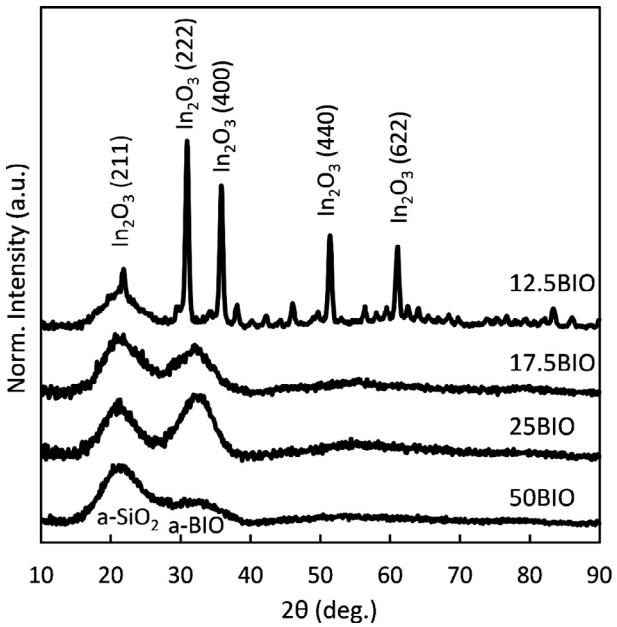

Fig. 1. GI-XRD patterns of BIO thin films on fused silica substrate, annealed at 500 °C.

Of the investigated compositions, the thin film with the lowest boron content to still be amorphous as-deposited is the 17.5BIO sample. STEM SAED of the 17.5BIO thin film is conducted to further verify the amorphous phase. The STEM image in Fig. 2(a) shows that a smooth and homogenous film is achieved. The sample is then heated in-situ to 400 °C (the maximum temperature of the instrument) and a SAED measurement is performed, as shown in Fig. 2(b). The absence of a crystalline diffraction pattern further confirms the amorphous nature of the 17.5BIO thin film even after heating to elevated temperatures.

The band gap is analyzed from optical spectroscopy using a Tauc plot, as shown in Fig. 3. The 50BIO thin film exhibits a large band gap of 4.44 eV. The band gap decreases gradually with decreasing boron content. The band gap of the 25BIO, 17.5BIO, and 12.5BIO thin films is 3.46, 3.19, and 2.97 eV, respectively. The trend of band gap versus boron content is summarized in Fig. 4(a). The polycrystalline 12.5BIO thin film has a band gap which is very similar to the band gap of ~2.9 eV for In_2O_3 [8]. This suggests that the 12.5BIO band gap is determined by the polycrystalline In_2O_3 phase.

Note that the amorphous phase stability and band gap as a function of boron content follow two distinctly different trends. The amorphous phase stability is near constant at ~500 °C over a wide range of BIO compositions (50BIO–17.5BIO) and then abruptly decreases to below 100 °C (*threshold* behavior). On the other hand, the band gap decreases almost linearly with decreasing boron content.

3.2. Device characterization

The structure of the staggered, bottom-gate device is shown in the inset of Fig. 4(b). BIO TFTs with a channel thickness (t_{ch}) of 50 nm and an O_2 partial pressure of 10% are fabricated for each composition. The sputtering time for the BIO channel layer is adjusted for each composition as the deposition rate significantly decreases with increasing boron content. This suggests that the target becomes more insulating at higher boron content which also