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Transparent oxide thin-film transistors using modulation-doped heterostructures

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1. Introduction

Since the first demonstration of thin-film transistors (TFTs) using amorphous $InGaZnO_4$, which is a transparent oxide semiconductor (TOS) with high electron mobility ~10 cm^2/V-s and high reliability compared to amorphous Si [1], transparent oxide TFTs with high carrier mobilities have been explored extensively [2]. As a method to achieve higher carrier mobilities, modulation doping, which has been effectively used for III-V semiconductors [3], is important. In fact, for TOSs, theoretical analysis [4] and natural formation [5] of modulation doping were reported. However, there are few experimental studies on designed modulation-doped heterostructures using TOSs. The purpose of this work is to investigate transparent oxide TFTs using n-$(In_2O_3)_{0.9}(SnO_2)_{0.1}$ / amorphous $InGaZnO_4$ (n-ITO / IGZO) modulation-doped heterostructures.

2. Experiments and Results

2-1. Energy band lineup of ITO / IGZO

Throughout this work, ITO and IGZO films were deposited using Ar-plasma sputtering under O_2 gas ambient. In order to investigate the energy band lineup of ITO / IGZO, we carried out transmittance measurements and UV photoemission spectroscopy (UPS). From the transmittance measurements of ITO and IGZO films on c-sapphire substrates, optical bandgap energies of ~3.6 eV for ITO and ~3.0 eV for IGZO are obtained. On the other hand, by the UPS of the ITO and the IGZO, it is found that the valence band energy maximum of ITO is higher than that of IGZO with a valence band discontinuity ΔE_V ~0.5-0.6 eV. It is reported that, for In_2O_3, the fundamental bandgap energy is ~0.8 eV smaller than the optical bandgap energy since the valence band energy maximum lies inside the optical bandgap [6]. We suppose the fundamental bandgap energy of ITO ~2.8 eV for our films and an energy band lineup of ITO and IGZO with conduction band discontinuity ΔE_C ~0.3-0.4 eV as shown in Fig. 1(a). Therefore, we expect to realize type II n-ITO / IGZO modulation-doped heterostructures as shown in Fig. 1(b), in which electrons transfer from n-ITO to IGZO and accumulate on the IGZO side at the heterointerface.

2-2. n-ITO / IGZO modulation-doped heterostructure

We deposited n-ITO (10 nm) / undoped-IGZO (340 nm) modulation-doped heterostructures on c-sapphire substrates as shown in Fig. 2(a). Figure 3 shows a cross sectional image of the heterostructure obtained by transmission electron microscope, in which a smooth heterointerface between poly-crystalline n-ITO and amorphous IGZO is confirmed. We investigated electron transport properties of the heterostructure using van der Pauw Hall measurements. For comparison, n-ITO (10 nm) / undoped-ITO (340 nm) (Fig. 2(b)) and n-IGZO (340 nm) (Fig. 2(c)) on c-sapphire substrates were also prepared and measured. Doping concentrations of all the structures were controlled by varying O_2 partial pressure during film deposition.

Figure 4 shows the relation between sheet electron concentration and electron mobility. We find that the modulation-doped heterostructures exhibit high electron mobilities ~40 cm^2/V-s in comparison with other structures. This mobility enhancement can be attributed to weaker electron scattering for the modulation-doped heterostructures, in which electrons are spatially separated from ionized donors in n-ITO. Moreover, for the heterostructures, we observed logarithmic temperature dependence of the conductance correction, which is a characteristic behavior for two-dimensional (2D) systems with both weak localization and electron-electron interaction, and thus indicates the 2D electron gas formation at the heterointerface.

2-3. Fabrication and characteristics of TFTs

We applied n-ITO / IGZO modulation-doped heterostructure to TFTs. Bottom-gate TFTs using the modulation-doped heterostructures were fabricated as follows. Using n-ITO (10 nm) / IGZO (30 nm) / SiO_2 (100 nm) / n-Si substrate, device mesas were isolated by dilute HCl etchant, followed by ohmic metallization for source and drain electrodes using Au (200 nm) / Ni (10 nm). For comparison, bottom-gate TFTs using IGZO (40 nm) / SiO_2 (100 nm) / n-Si substrate were also fabricated. Figure 5 shows schematics of TFTs. Channel length and width of TFTs are 10 μm and 100 μm, respectively. Output characteristics of TFTs are shown in Fig. 6. Comparing to IGZO TFT, much higher drain current ~20 mA/mm is obtained for n-ITO / IGZO TFT. Parameters of TFTs are listed in Table I, which indicates higher electron mobilities in n-ITO / IGZO TFTs than in IGZO TFTs.

3. Summary

Employing n-ITO / IGZO modulation-doped heterostructures, we confirmed enhancements of electron mo-

bilities and TFT performances. Modulation doping is a promising method for improvements of TFT characteristics using TOSs.

Acknowledgements

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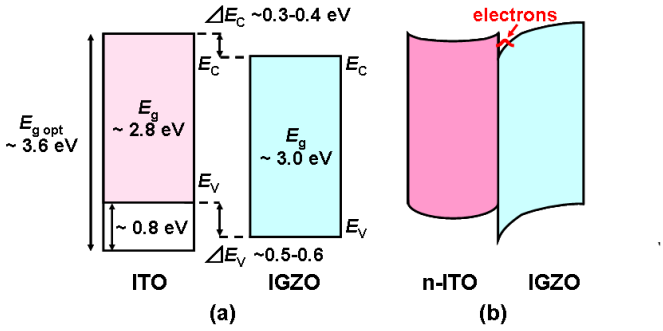

Figure 1. (a) Supposed energy band lineup of ITO and IGZO and (b) type II n-ITO / IGZO modulation-doped heterostructure.

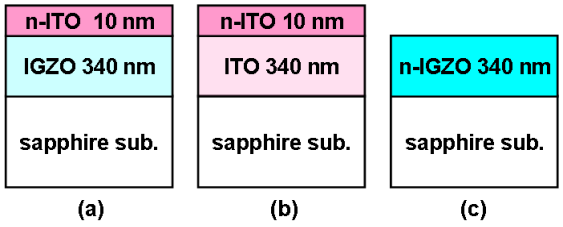

Figure 2. Sample structures (a) n-ITO/IGZO, (b) n-ITO/ITO, and (c) n-IGZO.

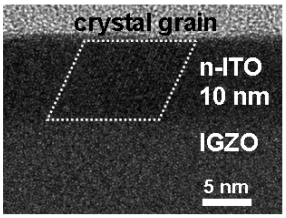

Figure 3. Cross sectional image of n-ITO / IGZO modulation-doped heterostructure obtained by transmission electron microscope.

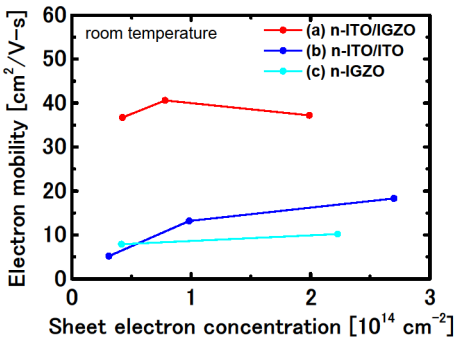

Figure 4. Relation between sheet electron concentration and electron mobility at room temperature.

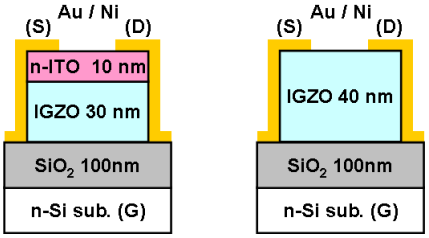

Figure 5. Schematics of n-ITO / IGZO modulation-doped heterostructure TFT and IGZO TFT, with source (S), drain (D), and gate (G) electrodes.

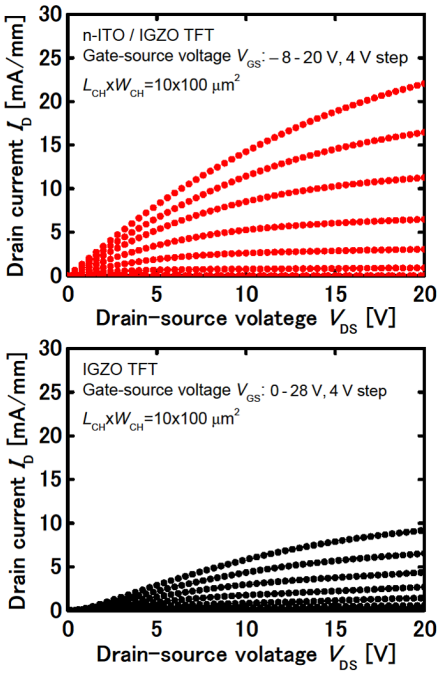

Figure 6. Output characteristics of n-ITO / IGZO TFT and IGZO TFT.

Table I. Parameters of n-ITO / IGZO TFT and IGZO TFT.

	Threshold voltage [V]	Mobility [cm²/V-s]	On-off ratio
n-ITO / IGZO TFT	-5.1	20	$>10^9$
IGZO TFT	2.2	7.5	$>10^8$