Electric Field Thermopower Modulation Analyses of Effective Channel Thickness of Amorphous $InGaO_3(ZnO)_m$ Thin Film Transistors

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ABSTRACT

Here, we analyzed the transistor characteristics of amorphous $InGaO_3(ZnO)_m$ thin film transistors (TFTs) by the electric field thermopower modulation, and found that the effective channel thickness of the TFTs varies from ~2 nm to ~28 nm depending on the m-value.

1 Introduction

In 2004, it has been demonstrated that a thin film transistor (TFT) using an amorphous transparent oxide semiconductor $InGaZnO_4$ (a-IGZO) as an active layer exhibits excellent transistor characteristics with a rather high field effect mobility (μ_{FE} ~7 $cm^2\ V^{-1}\ s^{-1}$), which is an order of magnitude higher than that of a-Si (~0.5 $cm^2\ V^{-1}\ s^{-1}$).[1] After that, several display companies energetically developed and commercialized large-sized liquid crystal displays (LCDs) and organic light emitting diode displays (OLEDs) using IGZO-based TFTs as the backplane.[2] Although IGZO-based TFTs are widely applied for the above purpose, μ_{FE} needs to increase because much higher-definition pixeled and wearable displays will be demanded in the future. Thus, alternate active materials that show much higher μ_{FE} need to be found.

In this study, we focused on amorphous $InGaO_3(ZnO)_m$ with higher *m*-values (a-$IGZO_m$ hereafter). It is known that crystalline $IGZO_m$ has a layered structure composed of InO_2^- layer and $GaO(ZnO)_m^+$ block alternately stack along the *c*-axis.[3,4] Nomura *et al.* precisely studied residual carrier concentration (n) and Hall mobility (μ_{Hall}) of the amorphous In-Ga-Zn-O system, and found that both n and μ_{Hall} increase with increasing *m*.[5] Orita *et al*. analyzed the conduction mechanism of a-$IGZO_m$ films and concluded that Zn 4s orbitals dominantly contribute to electron conduction of a-$IGZO_m$ with a large *m*-value.[6] However, the relationship between transistor characteristics of a-$IGZO_m$-based TFTs and *m*-value has not been clarified so far.

To address this issue, we attempted the electric field thermopower modulation analyses [7-11] to a-$IGZO_m$ TFTs. We measured the thermopower of a-$IGZO_m$ TFTs during a gate voltage application. We also measured the thermopower of $IGZO_m$ films. Then, we compared the sheet carrier concentration (n_{2D}) of $IGZO_m$ TFTs with the volume carrier concentration (n_{3D}) of $IGZO_m$ films when both show the same thermopower. Here, we show that the effective channel thickness (n_{2D}/n_{3D}) varied from ~2 nm to ~28 nm depending on the *m*-value.

2 Experimental

We fabricated $IGZO_m$-based TFTs (bottom-gate, top-contact type) on an alkaline-free glass substrate (0.7 mm thick, Corning® EAGLE XG®) using the following procedure. First, a 106-nm-thick AlO_x film, which served as the gate insulator, was deposited by atomic layer deposition (ALD) on an ITO-coated EAGLE XG substrate. The dielectric permittivity of the AlO_x film was 8. Then, ~20-nm-thick $IGZO_m$ film was deposited by PLD through a stencil mask. After that, the multilayer film was annealed at 350 °C in air for 5 min. Finally, Ti source/drain electrodes were evaporated.

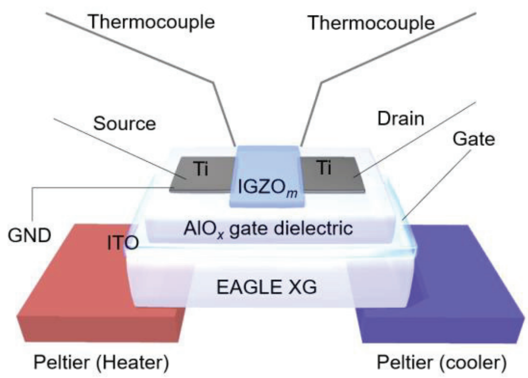

Figure 1. Schematic illustration of the electric field thermopower modulation of $IGZO_m$ TFTs at room temperature. The $IGZO_m$ TFT is placed between two Peltier devices. During the gate voltage application, thermopower is measured by applying temperature difference between the source and drain electrodes.

Standard transistor characteristics and thermopower modulation analyses of the resultant TFTs were performed at room temperature in air (**Fig. 1**). Detail of the thermopower modulation analyses has been published elsewhere.[7-11]

3 Results and Discussion

First, we fabricated IGZO$_m$ (m = 1, 2, 3, 4, 5, 7, 9, 10, and 30) films with varied oxygen pressure during the PLD to control the carrier concentration. We then checked the films by X-ray diffraction (**Fig. 2**) and found that the IGZO$_m$ films with $m \le 7$ were amorphous but the films with $m > 7$ were polycrystalline, similar to that Orita *et al.* who reported that IGZO$_m$ crystalizes even at room temperature when $m > 5$.[6]

The optical bandgap (data not shown) gradually decreased with increasing m-value (3.25 eV for m = 1 and 3.15 eV for m = 5). This tendency is similar to that of crystalline IGZO$_m$.[12] From these observations, we judged that a-IGZO$_m$ (m = 1, 2, 3, 4, 5, 7, 9, and 30) films were successfully fabricated.

Then, we measured the Seebeck effect and Hall effect of the films. **Figure 3a** plots thermopower (S) as a function of volume carrier concentration (n_{3D}) of the resultant IGZO$_m$ (m = 1, 2, 3, 4, 5, 7, 9, 10, and 30) films at room temperature in air. S-values are always negative confirming that the films are n-type semiconductors. The absolute value of S decreases with n_{3D} in all cases. Interestingly, all the plots are nearly located on a line that show the carrier effective mass (m^*) is 0.16 m_0. This indicates that the Zn 4s orbital dominated conduction band bottom exhibits similar band dispersion to that of In 5s orbital dominated conduction band bottom.

On the other hand, clear tendency was not observed in

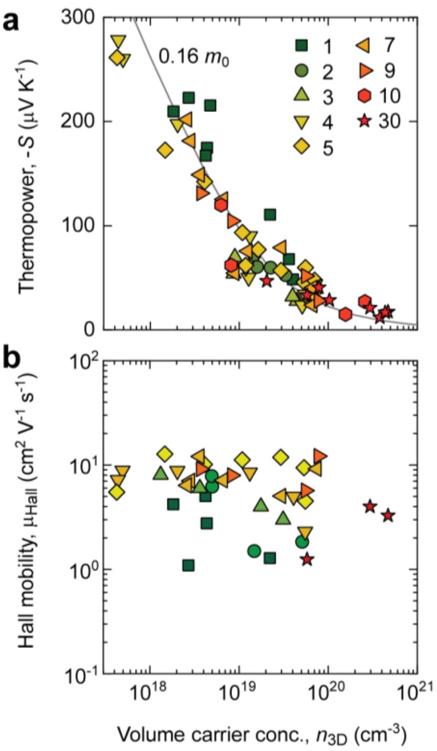

Figure 3. Electron transport properties of the a-IGZO$_m$ (m = 1, 2, 3, 4, 5, 7, 9, and 30) films at room temperature. (a) Thermopower vs. volume carrier concentration, (b) Hall mobility vs. carrier concentration. A clear trend is seen in (a) whereas there is no clear trend in (b).

μ_{Hall} as a function of n_{3D} **(Fig. 3b)**. Since m^* of all IGZO$_m$ films is similar, the difference in the observed μ_{Hall} is due to the difference in the carrier relaxation time (τ). Generally, τ strongly depends on the quality of the films. Thus, thermopower is a more reliable physical property to analyze the carrier transport properties than mobility.

Next, we fabricated IGZO$_m$ TFTs and measured the transistor characteristics. **Figure 4** shows typical transfer characteristics of IGZO$_m$ TFTs at room temperature. The channel length L was 100 μm and the channel width W was 400 μm. Drain voltage (V_d) of +5 V was applied in all cases. The on current gradually increases with m when $m \le 7$. However, when $m > 7$, the off current increases and the on current gradually decreases with m.

Figure 5 plots the field effect mobility (μ_{FE}) of the IGZO$_m$ TFTs. When $m \le 7$, μ_{FE} gradually increased with m, whereas it dropped with m when $m > 7$. Highest μ_{FE} was ~12 cm^2 V^{-1} s^{-1} obtained when m = 7. Since crystallization of IGZO$_m$ occurred when $m > 7$, origin of the low μ_{FE} of m = 10 and 30 would be the grain boundaries; carrier electrons are scattered at the grain boundaries. Finally, we measured thermopower of the TFT channel by applying various gate voltages. First, a constant V_g was applied to the TFT to accumulate carriers.

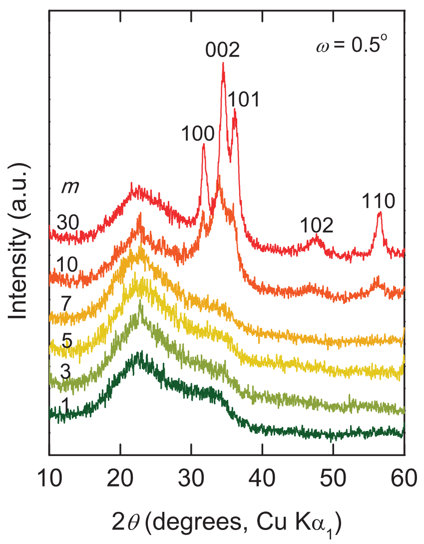

Figure 2. XRD patterns of the resultant IGZO$_m$ films. When $m \le 7$, a halo of IGZO$_m$ is seen at 2θ ~34°, whereas sharp diffraction peaks appear when $m > 7$.

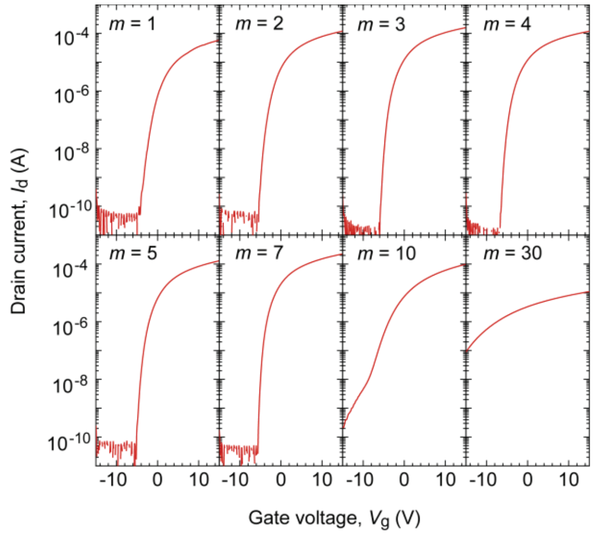

Figure 4. Typical transfer characteristics of IGZO$_m$ TFTs at room temperature. (L = 100 µm, W = 400 µm, V_d = +5 V) The on current gradually increases with m when $m \leq 7$. When $m > 7$, the off current increases and the on current gradually decreases with m.

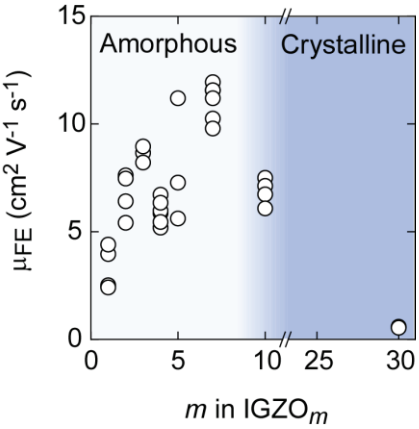

Figure 5. Field effect mobility (μ_{FE}) of the IGZO$_m$ TFTs. When $m \leq 7$, μ_{FE} gradually increases with m, whereas it drops with m when $m > 7$. Highest μ_{FE} is ~12 cm^2 V^{-1} s^{-1} obtained when m = 7.

Then, we measured thermopower of the TFT channel by applying various gate voltages (V_g). First, a constant V_g was applied to the TFT to accumulate electron carriers. Then, S of the channel was measured during the V_g application. **Figure 6a** plots electric field modulated S as a function of n_{2D}. The overall change in $|S|$ shows an upward trend when the n_{2D} is low (m = 1), and a decreasing tendency when the n_{2D} is high. The former is most likely due to the tail state around the conduction band bottom. The latter is a standard tendency. It should be noted that $|S|$ increases as the m-value increases. Then, we compared the n_{2D} (**Fig. 6a**) with n_{3D} **(Fig. 3a)** at the same

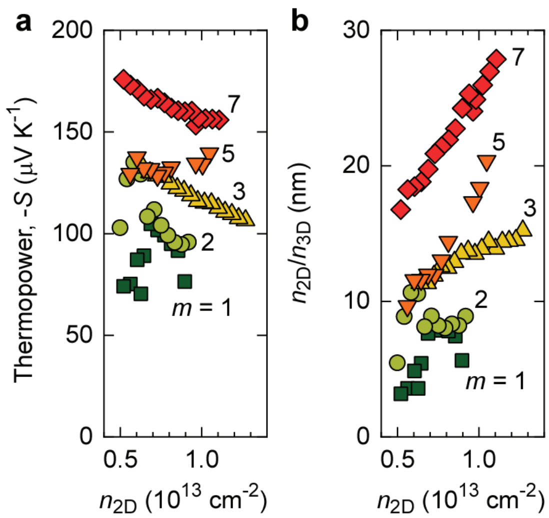

Figure 6. Electric field thermopower modulation analyses of the IGZO$_m$ TFTs. (a) Thermopower and (b) effective thickness of a-IGZO$_m$ TFTs as a function of n_{2D}. Note that effective thickness (n_{2D}/n_{3D}) varied from ~2 nm to ~28 nm depending on the m-value.

$|S|$ **(Fig. 6b)**. Interestingly, effective thickness (n_{2D}/n_{3D}) varied from ~2 nm to ~28 nm depending on the m-value. The overall tendency of n_{2D}/n_{3D} is increases with m-value. These results suggest that increase of effective channel thickness of IGZO$_m$ would enhance τ. This information may be useful to further improve IGZO$_m$-TFT characteristics in the future.

4 Summary

In this study, we attempted the electric field thermopower modulation analyses to clarify the relationship between transistor characteristics of IGZO$_m$ based TFTs and m-value. We found that the effective channel thickness of the IGZO$_m$ thin film transistors varied from ~2 nm to ~28 nm depending on the m-value. The overall tendency of n_{2D}/n_{3D} is first decreases with m-value and then increases with m-value. The increase of effective channel thickness of IGZO$_m$ would enhance τ. This information may be useful to improve IGZO$_m$ thin film transistor characteristics in the future.

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