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Suppression of Threshold Voltage Variation Due to Conduction Band Lowering Effect in Crystalline In-Ga-Zn-Oxide Thin Film Transistors

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1. Introduction

A c-axis aligned crystalline indium-gallium-zinc oxide (CAAC-IGZO) is an oxide semiconductor having a c-axis aligned crystalline structure [1]. The use of this material as an active layer of a thin film transistor (TFT) can achieve an extremely small off-state current [2] and high reliability, and its application to displays now attracts a great deal of attention [3]. In addition to the display application, we have proposed application of the CAAC-IGZO to LSIs such as a nonvolatile memory, a CPU, and an image sensor [4-6].

An IGZO TFT is an accumulation type device in which electrons serving as majority carriers are controlled by the gate voltage. However, a general IGZO film has n-type conductivity, and it is difficult to shift the threshold voltage of the TFT in the positive direction by impurity doping. Therefore, not only to improve the reliability but also to prevent the TFT from being normally-on, reduction in defect state density is important because they seem to be a factor producing an n-type active layer. By use of a CAAC-IGZO film, we have indeed succeeded in significantly reducing the defect state density, which can cause donor formation, as compared with an existing IGZO film [7].

In this work, we have reported that owing to a phenomenon named "conduction band lowering (CBL) effect", the threshold voltage of a TFT formed using an IGZO film with a sufficiently low donor concentration is converged on a certain low value.

2. Experiments

Fig. 1(a) shows I_d-V_g characteristics of CAAC-IGZO TFTs (6 samples) fabricated using CAAC-IGZO films with different donor concentrations as their active layers. Fig. 1(b) shows the relation between the threshold voltage V_{th} and the carrier concentration n at $V_g = 0$ V, which are estimated from the respective I_d-V_g characteristics. The simulation results obtained using the donor concentration N_d as a parameter are also plotted in Fig. 1(b) for comparison (described later). According to Fig. 1(b), even when the donor concentration of the CAAC-IGZO film is reduced, the positive shift of V_{th} is limited to a certain degree. Accordingly, TFTs each formed using a film with a sufficiently low donor concentration can have substantially uniform I_d-V_g characteristics and are turned on/off around $V_g = 0$ V.

Apparently, as the Fermi energy of a channel region of the IGZO TFT gets closer to the midgap, the energy barrier height (EBH), which electrons flowing between the source (S) and the drain (D) regions need to go over, becomes higher; when the Fermi energy reaches the midgap, the EBH seems to be half the bandgap ($E_g/2$ = 1.6 eV). However, the results in Fig. 1(b) indicate that, even when a film with a Fermi energy close to the midgap is used as an active layer of a TFT, its threshold voltage is not necessarily shifted in the positive direction.

In the following, we analyze the band structure in the channel length direction of an IGZO-TFT through numerical simulation. This analysis proved that the CBL effect contributes to the convergence of the I_d-V_g characteristics of IGZO TFTs each formed using a film with a sufficiently low donor concentration as shown in Fig. 1(a).

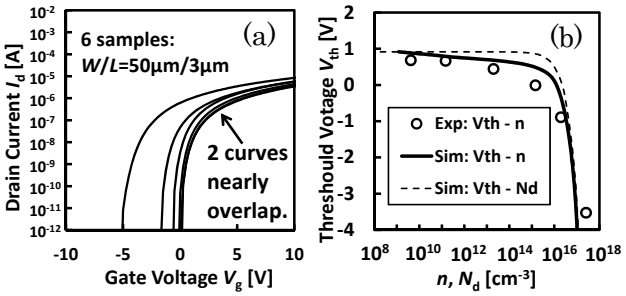

Fig. 1 (a) I_d-V_g characteristics of CAAC-IGZO TFTs (6 samples) fabricated using CAAC-IGZO films. (b) The relation between the threshold voltage V_{th} and the carrier concentration n at $V_g = 0$ V estimated from I_d-V_g characteristics. The open circle denotes a measured value ($V_{th} - n$). The solid line ($V_{th} - n$) and the dashed line ($V_{th} - N_d$) denote simulation results obtained using the donor concentration N_d as a parameter. Note that, even if the value of N_d is less than 10^9 cm^{-3}, the simulated value of n is saturated at 10^9 cm^{-3}.

3. Numerical Simulation

Fig. 2(a) shows a device structure of an IGZO TFT with an IGZO film thickness of 35 nm and a gate insulator EOT of 256 nm, corresponding to those of the device whose measurement results are shown in Fig. 1. First, we consider an n$^+$(S)- i(channel)-n$^+$(D) homo junction in the IGZO film. Fig. 2(b) shows simulation results of the conduction band structure on no bias condition along the dashed arrow in Fig. 2(a), i.e., in the channel length L direction, where L is 3 μm. The Fermi energy E_F is used as the origin of the energy level.

In the simulation, the EBH between the S/D regions is 0.58 eV. On the other hand, the EBH of a long-channel TFT is analytically derived as,

$$\mathrm{EBH} = e(\phi_m - \chi_{IGZO} - \frac{Q_{GI}}{C_{GI}}) - (\frac{1}{C_{GI}} + \frac{1}{2C_{IGZO}})e^2 N_d t \ . \ (1)$$

Here, ϕ_m denotes the work function of the gate electrode; χ_{IGZO}, the electron affinity of the IGZO film; Q_{GI}, the fixed charge in the gate insulator film; C_{GI}, the capacitance of the gate insulator film; C_{IGZO}, the capacitance of the IGZO film; t, the thickness of the IGZO film; and N_d, the donor concentration in the channel region. Eq. (1) is extended to a general value of N_d for the subsequent discussion. At this time, $N_d = n_i = 6.6\times10^{-9}\mathrm{cm}^{-3}$, and therefore the second term of eq. (1) is small enough to ignore.

Since the parameters used in the simulation of Fig. 3(b) are set to $e(\phi_m - \chi_{IGZO} - Q_{GI}/C_{GI}) = 0.58$ eV, the simulation result is consistent with eq. (1). This means that for the TFT, the EBH is lower than half the bandgap of bulk i-IGZO, $E_g/2 = 1.6$ eV. In other words, carrier density in the channel of the TFT increases more than that in the bulk i-IGZO film, due to electrons flowing from an n^+ region. We named this phenomenon "CBL effect".

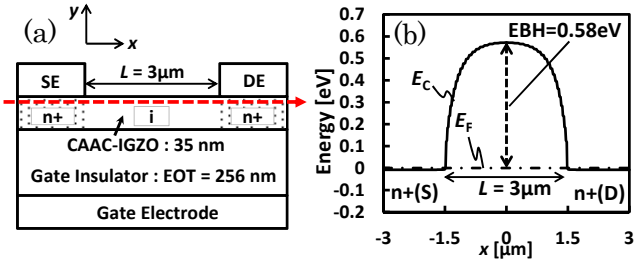

Fig. 2 (a) A cross-sectional view in the channel length direction of an IGZO TFT. (b) The conduction band structure on no bias condition along the dashed arrow in Fig. 2(a), i.e., in the channel length direction. The energy barrier height (EBH) between the S/D regions is 0.58eV.

Next, a change in the band structure with an increase in donor concentration N_d in the channel region is examined. Fig. 3(a) shows simulation results of the conduction band structure on no bias condition along the dashed arrow in Fig. 2(a), i.e., in the channel length direction. The value of N_d is varied from 6.6×10^{-9} cm^{-3} to 1×10^{18} cm^{-3}.

It is found from Fig. 3(a) that, when N_d is sufficiently low, no change occurs in the band structure and the EBH is constant due to the CBL effect. However, when N_d becomes too high ($N_d >> 10^{14}$ cm^{-3}), the EBH starts to decrease. Fig. 3(b) shows the N_d dependence of the EBH in the case of $e(\phi_m - \chi_{IGZO} - Q_{GI}/C_{GI}) = 0.58$ eV, and shows an approximate curve obtained by assigning values of N_d to eq. (1). Fig. 3(b) indicates that, when N_d is too high, the impact of the second term in eq. (1), which is proportional to N_d, leads to a decrease in the EBH. Such a lowering in the EBH due to the increase in N_d agrees with the negative shift of the I_d-V_g characteristics in Fig. 1(a).

As shown in Fig. 1(b), the relation between V_{th} and the carrier concentration n at $V_g = 0$ V, which is estimated from the simulation using N_d as a parameter, reproduces the tendency in the experiment. Fig. 1(b) also shows the simulated relation between V_{th} and N_d. As well as the EBH in Fig. 3(b), V_{th} is saturated at a certain value when N_d is sufficiently low. In other words, a sufficient reduction in donor concentration N_d leads to a device in which variation in threshold voltage of I_d-V_g characteristics is suppressed by the CBL effect.

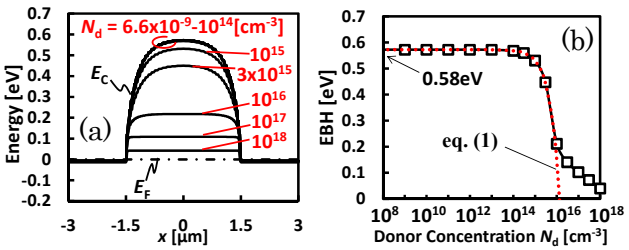

Fig. 3 (a) The donor concentration N_d dependence of the conduction band structure on no bias condition along the dashed arrow in Fig. 2(a), i.e., in the channel length L direction. (b) The N_d dependence of the energy barrier height (EBH). An approximate curve obtained by assigning N_d to eq. (1) is also shown, where $e(\phi_m - \chi_{IGZO} - Q_{GI}/C_{GI}) = 0.58$ eV is used.

4. Conclusions

By analyzing the band structure in the channel length direction of an IGZO-TFT through numerical simulation, we have found a phenomenon that the energy barrier is lowered by electrons flowing from an n^+ region to a channel region, i.e., the conduction band energy relative to the Fermi energy decreases. We have named the phenomenon "conduction band lowering (CBL) effect". Owing to this effect, even when the Fermi energy of an IGZO film gets closer to the midgap, a TFT formed using the film is always turned on around $V_g = 0$ V. In other words, by use of an active layer including an IGZO film with a Fermi energy close to the midgap, the CBL effect makes the threshold voltage of I_d-V_g characteristics converge into a certain low value and the characteristics variation can be suppressed.

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