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Analysis of Transfer Characteristics of InGaZnO Thin Film Transistors

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ABSTRACT

The analysis of transfer characteristics of InGaZnO thin-film transistors (IGZO TFTs) with a home-made-numerical calculation program presents information of the densities of defect, free carrier and fixed charge which are essentially useful for process evaluation.

1. INTRODUCTION

The TFTs for the FPD application have been actively researched and developed, and its performance has advanced dramatically. Amorphous silicon (a-Si), low temperature polycrystalline silicon (LTPS), and metal oxide semiconductor materials have been widely used for TFT fabrication. The oxide TFT is especially expected to be suitable for large and high-definition display at low cost [1-3]. Currently, flexible and stretchable displays have been actively developed on non-heat resistant substrates such as transparent and low cost resin [4]. The processing temperature lower than 300°C has been demanded. The fluorine terminated insulator film has been proposed as the reliable gate insulator formed below 300°C [5-7]. Moreover, analysis of performances of IGZO TFTs isolating the factors of defect density distribution, free carrier density and fixed charge density is important to establish the low temperature fabrication processing.

In this paper, we analyze experimental transfer characteristics of IGZO TFTs fabricated at 250°C by a home-made-numerical calculation program.

2. EXPERIMENT AND CALCULATION RESULTS

2-1. IGZO TFTs

Figure 1 shows the schematic processing steps of bottom-gate top-contact IGZO TFTs. (1) The n-type heavily doped (<0.007 Ωcm) crystalline silicon substrates coated with 100-nm-thick thermally grown SiO_2 were prepared as the gate electrodes and gate insulators. (2) Next, a-IGZO (In:Ga:Zn =1:1:1) films with a two-layered structure were deposited at room temperature by Induction coupled plasma (ICP) induced sputtering system with different O_2 / Ar gas ratio conditions [8, 9]. The 45-nm-IGZO layers were first deposited directly on the thermally grown SiO_2 surface with pure Ar gas. The gas pressure was 0.9 Pa, the input RF power was 7000 W, and target voltage was -400 V. The 5-nm-IGZO layers were additionally formed on the first IGZO layers with Ar and O_2 mixed gasses at an O_2 / Ar mixing ratio of 5% by rapid O_2 injection. The gas pressure, the input RF power, and target voltage kept the initial values. (3) Mo source and drain electrodes were formed by photolithography, and lift-off process. No passivation film was formed. (4) The TFTs with a 10-μm channel length and channel width 90-μm were finally formed. They were heated at 250 °C for 2 h under the O_2 gas atmosphere.

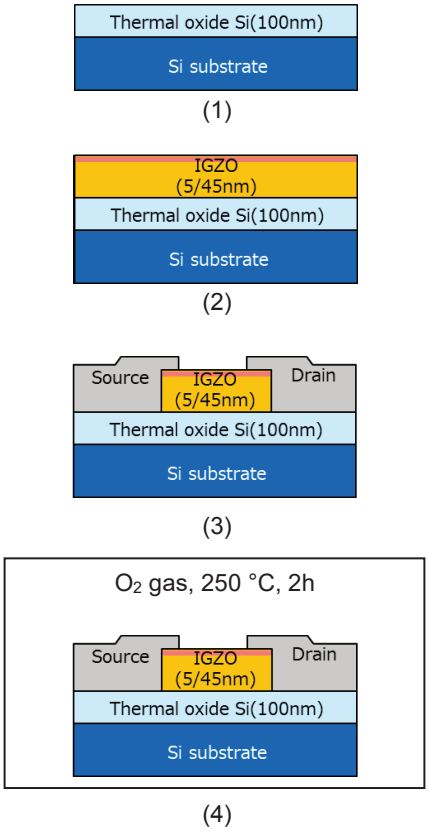

Fig. 1 Schematic processing steps of fabrication of IGZO TFTs

2-2. Numerical calculation model

Experimental transfer characteristics of IGZO TFTs were analyzed by a home-made-numerical calculation programed used with the finite-element method combined with statistically thermodynamic conditions with defect states which localized at thermal grown SiO_2 / IGZO (bottom) and IGZO / air (top) interfaces as well as distributed spatial-uniformly in the IGZO films [10]. Two types of carrier-trap-defect states were introduced. One is the deep level carrier-trap-defect states localized at the mid gap in the 3.1-eV-wide band gap with their density distribution given by the Gaussian function. The other one is the tail-type-carrier-trap-defect states, whose density exponentially decreased from the conduction band edge to the mid gap with two specific energy constants. The donor sites owing to oxygen vacancies were also programed uniformly in the IGZO films. Finally, the oxide fixed charge was given at the SiO_2 / IGZO interface.

2-3. Experimental transfer characteristics and their analysis

After confirming the ohmic characteristics in the output characteristics with a drain voltage V_d of 0.1 V and a gate voltage V_g of 1 V, the transfer characteristic was measured with V_g ranging from -10 to 15 V at V_d of 0.1 V, as shown in Fig.2. Low leakage currents less than 10^{-12} A were successfully obtained for V_g lower than -1.3 V. The drain current sharply increased from 2.0×10^{-13} to 2.5×10^{-8} A as the V_g increased from -1.3 to 0 V as shown by logarithmically plotted experimental drain current as a function of the gate voltage in Fig.2(a). The drain current does not increase proportionally to V_g from 0 to 6 V, as shown by linearly plotted experimental drain current as a function of the gate voltage in Fig.2 (b). It means that the carrier generation ratio caused by gate voltage application. The super-linear increase in the drain current suggests that the carrier generation ratio gradually increased as V_g increased from 0 to 6 V.

The experimental transfer characteristic was numerically analyzed. The slightly depleted characteristic of the experimental drain current was well recreated with the calculated drain current widely ranging from 1×10^{-13} to 4×10^{-6} A, as shown by red curve in Fig. 2. The best agreement of the calculated transfer characteristic to experimental one results in the type of defect states, its density, free carrier density, and carrier mobility.

The fitting process shown in Fig. 2 suggested following fundamental properties: (1) The IGZO film was conductive with a donor density of 1.5×10^{12} cm^{-2}. (2) The film also had tail-type-carrier-trap-defect states with a density of 1.4×10^{12} cm^{-2} expressed by double-exponential function as $5.0\times10^{11}\exp(-E/1.2) + 5.0\times10^{12}\exp(-E/0.15)$ (cm^{-2} eV^{-1}), where E (eV) is the energy in the band gap measured from the conduction band edge, as shown in Fig.3. The total density of 1.4×10^{12} cm^{-2} in 50 nm-thick IGZO film corresponds to volume density of 2.7×10^{17} cm^{-3}.

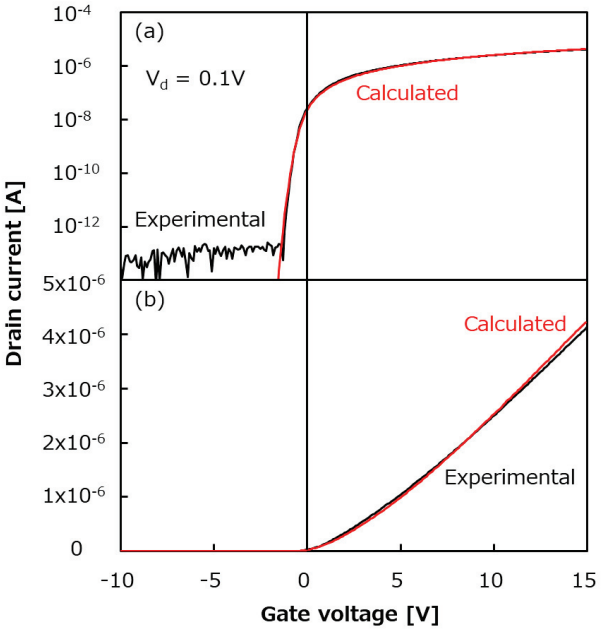

Fig. 2(a) Logarithmically plotted experimental (black curve) and calculated (red curve) drain currents as a function of the gate voltage and (b) linearly plotted ones.

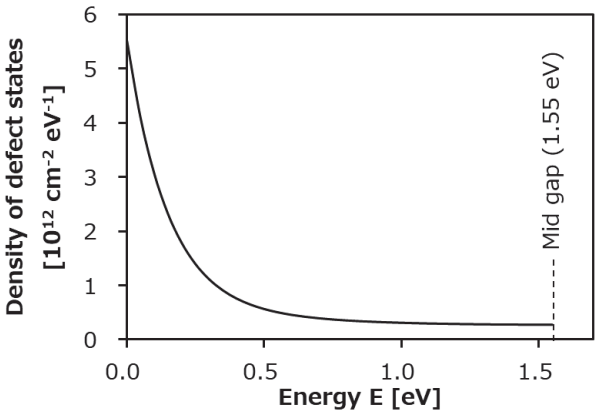

Fig. 3 Calculated energy distribution of density of tail-type-carrier-trap-defect states of IGZO film

(3) The IGZO/air surface with no passivation film had a carrier-trap-defect states localized at the mid gap with a density of 8.5×10^{11} cm^{-2} with a peak defect density of 5.3×10^{12} cm^{-2} eV^{-1} and an energy width of 0.18 eV for Gaussian distribution. The trapping electron carriers in the IGZO film at the IGZO / air surface played a role in keeping the slightly depleted transfer characteristic. (4) There was no significant defect state at thermal grown SiO_2 / IGZO interface, which had no oxide fixed charge either. (5) The carrier mobility of IGZO film was 9 cm^2 / Vs.

The sharp increase in the drain current for gate voltage ranging from -1.3 to 0 V suggests the SiO_2 / IGZO interface formed well with low density of carrier-trap-defect states in deep energy levels of its band gap. The drain current subsequently had a characteristic of super-linearly increasing for the gate voltage ranging from 0 to 6 V. For zero bias condition, the carrier-trap-defect states in the IGZO film was already occupied partially by the electron carriers generated by the donor sites. The carrier trapping rate for the tail-type defect states gradually decreased from 1.5 x 10^{11} cm^{-2} V^{-1} to 0 as the gate voltage increased from 0 to 6 V. Consequently, the density of electron carriers accumulated at the SiO_2 / IGZO interface super-linearly increased from 1.9 x 10^{10} to 1.0 x 10^{12} cm^{-2} as the gate voltage increased from 0 to 6 V.

4. CONCLUSIONS

The TFTs were fabricated in two layered 50-nm-thick IGZO films on thermal grown 100-nm-thick SiO_2 insulators formed on the heaty doped silicon substrates as the gate electrodes. The IGZO films were formed by ICP sputtering with pure Ar gas for the first 45 nm and then O_2 and Ar mixed gasses for the second 5 nm. Experimental transfer characteristics at the drain current of 0.1 V had a slight depletion mode with the leakage current lower than 10^{-12} A, sharp increase in the drain current from 2.0x10^{-13} to 2.5x10^{-8} A for V_g between -1.3 and 0 V, and super-linear increase in the drain current for V_g between 0 and 6 V. The numerical analysis of the experimental transfer characteristics resulted in the facts of the conductive IGZO films with (1) a donor density of 1.5 x 10^{12} cm^{-2} and (2) tail-type-carrier-trap-defect states with a density of 1.4 x 10^{12} cm^{-2} expressed by double-exponential function, (3) the IGZO / air surface with the carrier-trap-defect states localized at the mid gap with a density of 8.5 x 10^{11} cm^{-2}, (4) the thermal grown SiO_2 / IGZO interface There was no significant defect state with no oxide fixed charge, and (5) the carrier mobility of 9 cm^2 / Vs. The sharp increase in the drain current resulted from the good SiO_2 / IGZO interface. The trapping electron carriers in the IGZO film at the IGZO / air surface played a role in keeping the slightly depleted transfer characteristic. The super-linear increase in the drain current for V_g between 0 and 6 V resulted from that the carrier trapping rate for the tail-type defect states gradually decreased from 1.5 x 10^{11} cm^{-2} V^{-1} to 0 as the gate voltage increased from 0 to 6 V.

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