Extended Abstracts of the 2010 International Conference on Solid State Devices and Materials, Tokyo, 2010, pp307-308

Impedance analysis of controlled-polarization-type ferroelectric-gate TFT using RC distributed constant circuit

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1. Introduction

Recently, ferroelectric-gate field-effect transistors (FETs) have attracted much attention because they have several advantages such as nonvolatility, fast and nondestructive readable operation, capability of high-density integration and low power consumption. The ferroelectric-gate FETs with a metal-ferroelectric-insulator-silicon structure have been developed and nonvolatile memory operation and long memory retention time have been reported. However, metal-ferroelectric-insulator-silicon structure have disadvantage on lowering the operation voltage due to the existence of the insulator layer. Hence, the use of an oxide semiconductor was proposed as another way to obtain a good interface between ferroelectric and semiconductor. However, ferroelectric-gate TFT using oxide semiconductor channel usually operates at accumulation-depletion mode, because most of oxide semiconductor dose not form inversion layer. This indicates that the charge density of the oxide semiconductor in depletion condition is much lower than the spontaneous polarization of typical ferroelectric material. It can be expected that this charge mismatch causes difficulty of polarization switching of the ferroelectric layer and so on.

To solve the issue of charge mismatch, we propose novel ferroelectric-gate thin films transistors (TFTs) using an interaction between the spontaneous polarization of a polar semiconductor (P_{SPS}) and a ferroelectric layer (P_{SFe}), which is named a controlled-polarization-type ferroelectric-gate TFTs [1,2]. The controlled-polarization-type ferroelectric-gate TFTs which have metal-ferroelectric-semiconductor (MFS) structure were fabricated using ZnO channel as the polar semiconductor and an $YMnO_3$ film as the ferroelectric gate. Although nonvolatile memory operation is observed on the ferroelectric-gate TFT with ZnO/$YMnO_3$ structure [1,2], the state of the channel and distribution of the carrier concentration was not revealed.

In case of TFTs with a paraelectric gate insulator, the carrier concentration in the channel changes gradually from source to drain. On the other hand, in case of TFTs with a ferroelectric gate insulator, the carrier concentration is controlled by P_{SFe}, which indicates the carrier concentration depends on the domain structure of the ferroelectric layer. Therefore, it can be expected that the carrier concentration and transistor operation of TFTs with a ferroelectric gate insulator is more complicated than that with a paraelectric gate insulator. To investigate the distribution of the carrier concentration in the channel of the ferroelectric-gate TFT with ZnO/$YMnO_3$ structure with a ferroelectric gate insulator, impedance spectra of was measured and analyzed using TFT model shown in Fig. 1(a), because TFT express by RC distributed constant circuit at high frequency region.

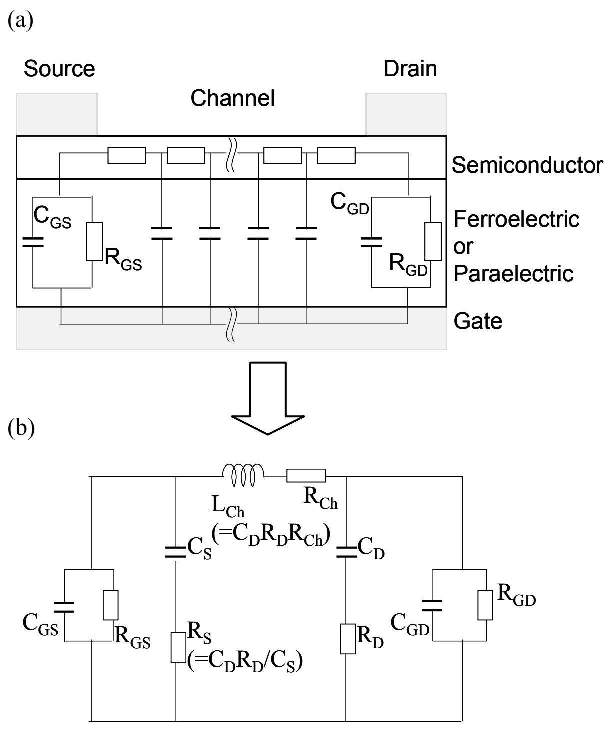

Fig.1 RC distributed constant circuit and equivalent circuit

2. Results and Discussion

The impedance spectra for the TFT model with the RC distributed constant circuit shown in Fig. 1(a) was calculated by SPICE. The obtained impedance spectrum is analyzed by the equivalent circuit of the TFT model shown in Fig. 1(b) [3]. C_S and C_D in the equivalent circuit correspond with the capacitances of the channel region near source and drain electrodes. Since the capacitance of the channel in Fig. 1(a) is a total of C_S and C_D, the change of the distribution of the carrier concentration can be evaluated by the ratio of C_S and C_D. Figure 2 shows the calculated results of C_S, C_D and the channel resistance at various channel condition. When the channel resistance is low (Fig.2(a)), the ratio of C_S and C_D are 82 % and 18 %, respectively. This result indicates that the region corresponding to C_S expands when the channel resistance is low. Moreover, the ratio of C_S and C_D were calculated in the cases of high channel resistance (Fig.2(b)), gradual change of resistivity, which corresponds the channel of the paraelectric-gate TFT (Fig.2(c)), and steep change of resistivity, which corresponds the channel of the ferro-electric-gate TFT (Fig.2(d)). The results indicate that the C_S region expands when the channel resistance is low, and the C_S region shrinks when the channel has high resistance or gradual change of resistivity. When the channel has steep change of resistivity, the C_S region of element shrinks greatly than the other channel conditions. Therefore it was found that this change of C_S is peculiar phenomenon in ferroelectric-gate TFT.

Then, impedance spectra of the ferroelectric-gate TFT with $ZnO/YMnO_3/Pt/YSZ$ structure were measured in Fig. 3(a). The carrier concentration of ZnO was 1.5×10^{16} cm^{-3}. The gate voltage was changed from -4 V to 4 V, and the impedance spectra were measured between the source and gate electrodes. The fitting was carried out using the equivalent circuit shown in Fig. 1(b). The result is shown in Fig. 3. The sum of C_S and C_D is not constant because relative permittivity of ferroelectric is depends on applied voltage and the electrode area expands when channel is accumulated. While C_D is almost independent on the gate voltage, C_S decreases with decreasing the gate voltage. The decrease of C_S at negative gate voltage region indicates that the increase of resistivity in the channel is occurred only at the region near the source electrode, which suggests that P_{SFe} of $YMnO_3$ is switched only at the region. On the other hand, the increase of C_S at positive gate voltage region indicates that the decrease of resistivity in the channel is occurred at entire channel region.

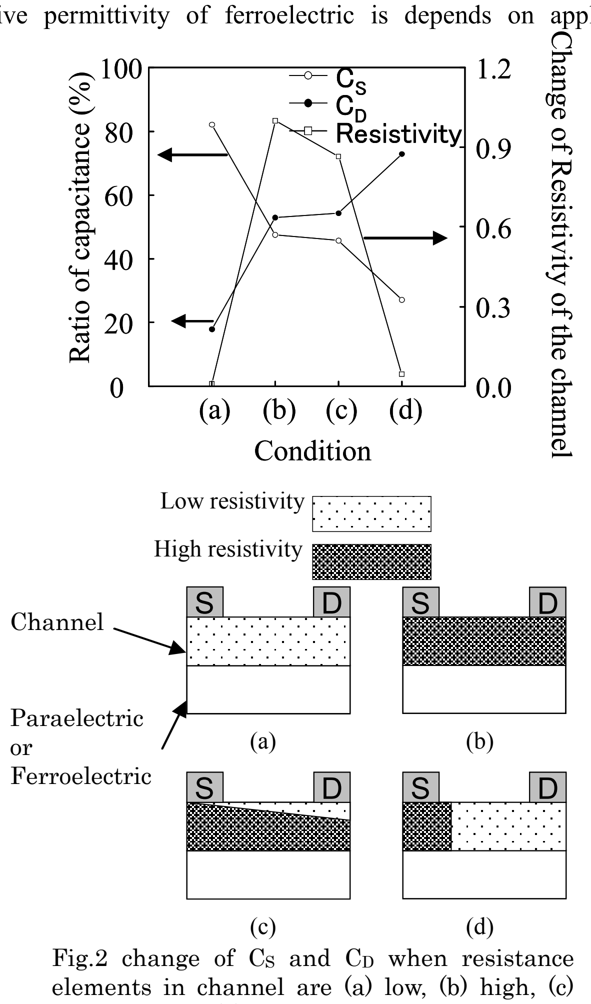

Fig.2 change of C_S and C_D when resistance elements in channel are (a) low, (b) high, (c) gradually and (d) steep resistivity

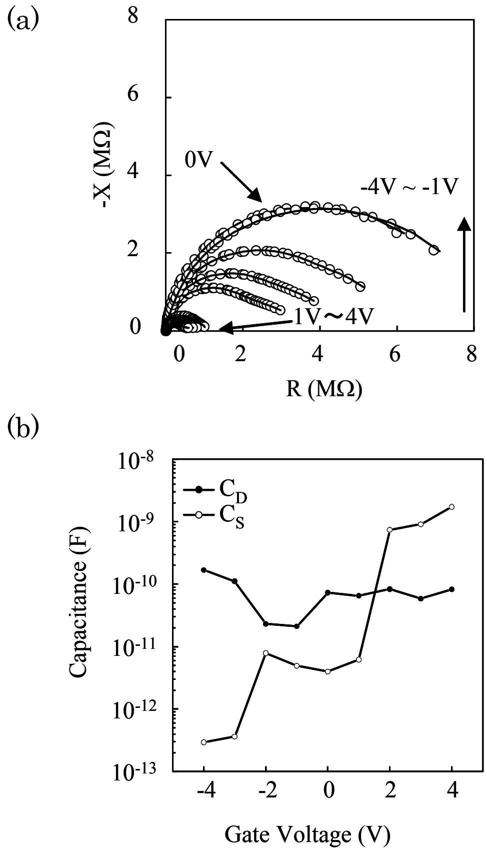

Fig.3 (a) Impedance spectra and fitting results (b) fitting results of C_S and C_D in the channel on the gate voltage

3. Conclusions

The impedance analysis using RC distributed constant circuit is applicable to analysis of the channel condition of ferroelectric-gate TFT. The results suggests that the reversal of P_{SFe} for $YMnO_3$ was occurred only at the region near the source electrode by negative gate voltage, and entire channel region becomes low resistivity state by positive gate voltage.

References

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