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Two-Dimensional Electron Gas Switching in an Ultra Thin Epitaxial ZnO Layer on a Ferroelectric Gate Structure

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1. Introduction

Nonvolatile memories based on metal ferroelectric semiconductor field effect transistors (MFSFETs) are highly attractive because, in contrast to conventional ferroelectric capacitor memories, the memory cell size is scaled only by the FET dimensions [1]. However, realization of MFSFETs has faced difficulties in controlling the ferroelectric and semiconductor interface, which is vital to good retention characteristics. Growing the ferroelectric gate directly on the silicon substrate resulted in unstable channel characteristics due to the existence of interface oxide layers. Although channel stabilization is possible by inserting a buffer layer between the ferroelectric and the silicon substrate [2], a built-in potential across such a stacked structure gives rise to a depolarization field and leakage currents which are detrimental to the retention properties.

In this paper, we demonstrate excellent retention property of an MFSFET comprising a high quality heteroepitaxial structure of an ultra thin ZnO and a ferroelectric gate layers (Fig.1). Because of the excellent or nearly atomically flat semiconductor (ZnO)/ferroelectric interface, switching of two-dimensional electron gas between accumulation and depletion states is successfully realized. An extremely high on/off ratio of the drain current is higher than 10^6. In addition, this high on/off ratio is retained at 10^4 even after 10^5 s.

2. Experimental

A $SrTiO_3$ (001) single crystal (STO) was used as a substrate. Stacked films of a 30-nm-thick $SrRuO_3$ (SRO) film (gate electrode), a 450-nm-thick $Pb(Zr,Ti)O_3$ (PZT) film and a 30-nm-thick ZnO film were sequentially deposited on the STO substrate by pulsed laser deposition (PLD) at 700, 700 and 400°C, respectively. Metal (Pt/Ti) source and drain contacts were formed on the ZnO film.

3. Results and Discussion

The crystallinity and crystallographic orientation of the grown films were evaluated by cross-sectional transmission electron microscopy (TEM) and X-ray diffraction (XRD). Figure 2 shows the TEM images of a Pt/Ti/ZnO/PZT/SRO/STO structure. Since there is no undesirable layer at the ZnO/PZT interface and the ZnO apparently keeps the periodic lattice structure on the single crystal PZT, excellent physical and electrical properties of the ZnO/PZT interface are expected. Figure 3 shows an XRD profile of the ZnO/PZT/SRO/STO structure. The SRO, PZT and ZnO films are preferentially oriented along (00*l*), (00*l*) and (11-20) directions, respectively. In addition, the transmission electron diffraction (TED) pattern from a stacked ZnO/PZT area (Fig. 4) shows diffraction spots related to single crystal lattices. Thus, we can reasonably conclude that the ZnO grows epitaxially on the PZT/SRO/STO structure. It should be emphasized that the *c*-axis of the ZnO film, along which a spontaneous polarization appears, is perpendicular to the polarization axis (*c*-axis) of the PZT film. Accordingly, the spontaneous polarization in ZnO does not inhibit the polarization switching of PZT.

The carrier density of ZnO films with different thicknesses prepared on the PZT/SRO/STO samples are shown in Fig. 5. The carrier density decreases with reduction of the film thickness and is about 10^{15} cm^{-3} at 30 nm, which is much lower than those in previous reports [3]. We believe that such a low carrier density is due to the epitaxial growth of defect free ZnO.

Ferroelectric hysteresis (*P*-*V*) measurements were made on a Pt/Ti/ZnO/PZT/SRO capacitor with the 30-nm-thick ZnO layer (Fig. 6). The remnant polarization (P_r) of the capacitor is 30 $\mu C/cm^2$, which is sufficient to deplete the entire electrons across the ZnO layer. Capacitance-voltage (*C*-*V*) measurements revealed the charge response of the Pt/Ti/ZnO/PZT/SRO structure against the applied voltage (Fig. 7). We also characterized a Pt/Ti/PZT/SRO structure as a reference. When positive voltages are applied to the SRO electrode, the capacitance of the ZnO/PZT layers is similar to that of the reference structure. This fact indicates that two-dimensional electron gas is accumulated at the ZnO/PZT interface because the ZnO layer has no contribution to the total capacitance in series. When negative voltages are applied to the SRO electrode, in contrast, the total capacitance is reduced as a result of full depletion of the ZnO layer. These accumulation and depletion states were preserved even when the applied voltage was removed.

The subthreshold characteristics (I_{ds}-V_{gs}) of an MFSFET with the Pt/Ti/ZnO/PZT/SRO structure are shown in Fig. 8. The drain current shows a counterclockwise hysteresis loop, corresponding to the ferroelectric polarization switching. The maximum and the minimum drain currents were obtained with the gate bias of +10 and -5 V, respectively. The ratio of these currents is higher than 10^6.

The retention characteristics of the MFSFET have been investigated at room temperature. First, the MFSFET was biased with V_{gs} = +10 V for setting an on-state or V_{gs} = -10 V for setting an off-state, respectively. Then, the device state was probed by drain current measurements as a function of retention time. As shown in Fig. 9, no significant change in I_{ds} was observed in the off-state. As a result, the on/off ratio of the drain current was initially 10^6 and it was greater than 10^4 even after 10^5 s. Extrapolation of the retention behavior predicts a definite split of I_{ds} over 10 years.

The stable on- and off-states are expected from physical insights of the developed structure. In the on-state, electrons in ZnO are easily accumulated at the ZnO/PZT interface owing to direct coupling to the ferroelectric polarization without generating a depolarization field [4]. On the other hand, because the electron density of the ZnO layer is low enough, the conductivity of fully depleted ZnO layer is extremely low in the off-state. Thus, the high on/off ratio can be maintained for such a long time.

4. Conclusions

We demonstrated a two-dimensional electron accumulation and complete depletion switching operation using an ultra thin ZnO with an extremely low carrier density (~10^{15} cm^{-3}). As a result, a high on/off ratio of drain current more than 10^6 was realized. A long retention time longer than 10^5 s with the on/off ratio of 10^4 was achieved.

References

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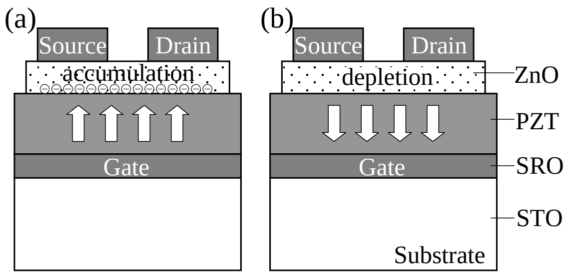

Fig. 1 Schematics of (a) an on-state (two-dimensional electron accumulation) and (b) an off-state (electron depletion) of an MFSFET.

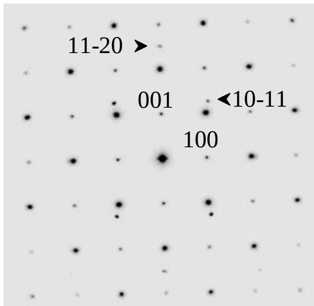

Fig. 4 TED spots related to the plane indices of ZnO (arrows) and PZT.

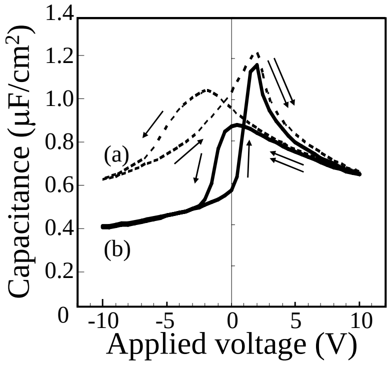

Fig. 7 *C-V* characteristics of (a) Pt/Ti/PZT/SRO and (b) Pt/Ti/ZnO/PZT/SRO capacitor.

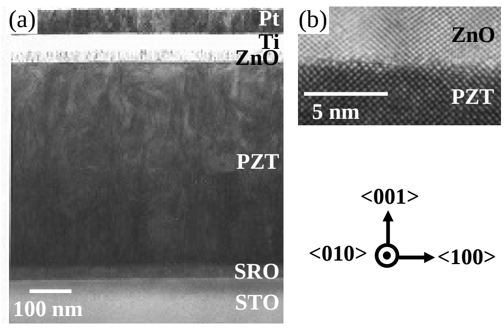

Fig. 2 Cross-sectional TEM images of (a) a Pt/Ti/ZnO/PZT/SRO/STO structure and (b) higher magnification of the ZnO/PZT interface.

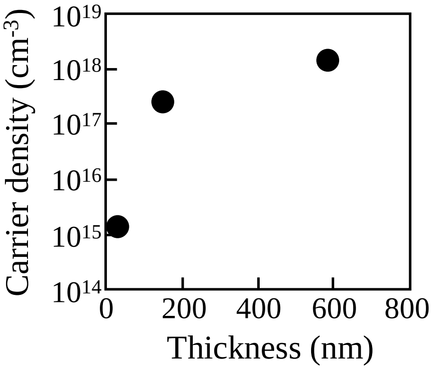

Fig. 5 Carrier density of ZnO films as a function of the film thickness.

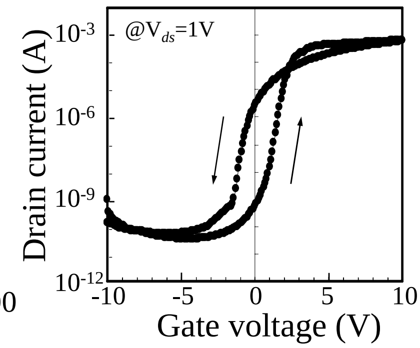

Fig. 8 I_{ds}-V_{gs} characteristics of an MFSFET using a ZnO thin film.

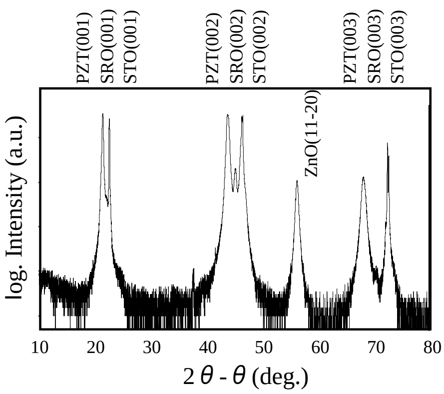

Fig. 3 XRD spectra from a ZnO/PZT/SRO/STO structure.

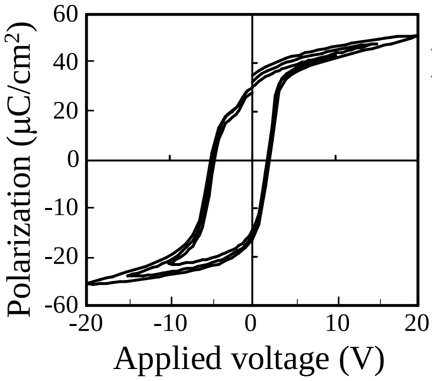

Fig. 6 *P-V* hysteresis curves of the Pt/Ti/ZnO/PZT/SRO capacitor.

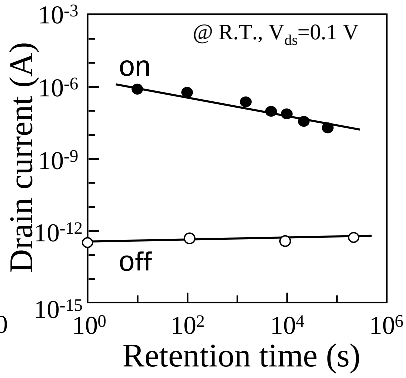

Fig. 9 Retention characteristics of the MFSFET.