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Electrical Characterization of $YMnO_3$-based Metal-Ferroelectric-Insulator-Semiconductor Capacitor by Novel Method

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We proposed an $YMnO_3/Y_2O_3/Si$ structure for Metal/Ferroelectric/Insulator/Semiconductor (MFIS) type ferroelectric gate field effect transistor (FET), because $YMnO_3$ has suitable properties for this application such as small spontaneous polarization and low permittivity. The epitaxially grown $Pt/YMnO_3/Y_2O_3/Si$ capacitors showed ferroelectric-type hysteresis on capacitance-voltage characteristics. Although the memory retention time of the as-deposited capacitors was 10^3 s, it was prolonged up to 10^4 s when the leakage current density was reduced from 4×10^{-8} A/cm^2 to 2×10^{-9} A/cm^2 by annealing under N_2 ambience. It was found that the dominant leakage mechanisms at high and low electric field were Poole-Frenkel emission from the Y_2O_3 layer and ohmic conduction, respectively. This result indicates that the leakage current was limited by the Y_2O_3 layer at high electric field and was mainly dominated by the number of defects in the $YMnO_3$ layer at low electric field. From the pseudo isothermal capacitance transient spectroscopy (ICTS), the trap density was determined as an order of 10^{15} cm^{-3}. Since the variation of the leakage current by annealing was observed only in the low electric field region, it is suggested that the retention characteristics of $Pt/YMnO_3/Y_2O_3/Si$ capacitors were influenced by the number of defects in the $YMnO_3$ layer.

Key words: Ferroelectric-gate FET, retention characteristics, leakage current, Poole-Frenkel emission, isothermal capacitance transient spectroscopy (ICTS)

1. INTRODUCTION

Ferroelectric gate field-effect transistors (FETs) were investigated for applications to nonvolatile memory devices due to the nondestructive read operation and the advantages of decreasing memory cell size.[1,2] Because of the difficulty to obtain an excellent ferroelectric-semiconductor interface, ferroelectric gate FETs with a metal-ferroelectric (-metal)-insulator-semiconductor (MF(M)IS) structure have been widely studied.[3-5]

Recently, long memory retention characteristics (> 10^4 s) have been reported.[5] This progress reveals the relationship between the retention characteristics and the leakage current of the MFIS capacitor. It has been reported that Schottky current has affected retention characteristics.[6] Since retention characteristics depend on the retained charge density in the ferroelectric layer, it is possible that the leakage current influences retention characteristics. When the space charge is rearranged inside of the ferroelectric layer so that the polarization of the ferroelectric layer is neutralized, the polarization apparently disappears although it is stall retained.

Although the stability of the polarization of a ferroelectric thin film on a semiconductor has not yet been clearly understood, it is obvious that to reduce the depolarization field, enlargement of the capacitance per unit area of insulator layer, the coercive electric field of the ferroelectric films, and thickness of the ferroelectric films are required.[7-11] Given the device application, the former two are important because an increase of the thickness results in an increase of the switching voltage.

We investigated $YMnO_3/Y_2O_3/Si$ structure for MFIS type ferroelectric gate FET. Since $YMnO_3$ has relatively small spontaneous polarization (5 μC/cm^2) and low permittivity (ε_r=20), it can be expected that a large depolarization field is not generated and that high voltage is not required to polarize $YMnO_3$ fully.[12,13] We succeeded in fabricating $YMnO_3$ epitaxial films with a remanent of 4.2 μC/cm^2 on (111)Pt/sapphire substrates and epitaxially grown $(0001)YMnO_3/(111)Y_2O_3/(111)Si$ capacitors with ferroelectric type C-V hysteresis.[14,15] We also have developed pulsed C-V measurement and low frequency D-E measurement for MFIS capacitor to investigate the effects of space charge and polarization characteristics. The details of these developments are described elsewhere.[12,16]

In this paper, the electrical properties of $Pt/YMnO_3/Y_2O_3/Si$ capacitors are characterized. By analyzing leakage current and capacitance-time characteristics, the influence of the leakage current on the retention characteristic of the $Pt/YMnO_3/Y_2O_3/Si$ capacitors is discussed in detail.

2. EXPERIMENT

N-type Si(111) single crystal wafers with 1 Ω·cm resistivity were used as substrates. The substrates were chemically cleaned by RCA treatment and 1% HF acid. After the cleaning, Y_2O_3 epitaxial films with a thickness of 20 nm and $YMnO_3$ films with a thickness of 400 nm were deposited on the Si substrates by a pulsed laser deposition (PLD) method (ULVAC, ULP-1000) with an eximer laser (Lambda Physic) operated at the wavelength of 248 nm. Details of the deposition of the $YMnO_3/Y_2O_3/Si$ capacitors are described elsewhere.[17] Top Pt electrodes were deposited by an rf magnetron sputtering deposition system through a shadow mask. The capacitance was measured using an LCR meter (HP 4284A). The leakage current was measured using a pico-ampere meter (HP 4140B). The retention characteristics of the MFIS capacitors were obtained by the change in the capacitance at the middle of the memory window. The retention time was defined when the difference of the capacitance after being charged by the positive and negative electric field became 50%.

3. RESULTS AND DISCUSSION

Figure 1 shows a C-V characteristic of an epitaxially grown $YMnO_3/Y_2O_3/Si$ capacitor. The C-V characteristic shows ferroelectric type hysteresis with the memory window saturated at ±13 V. Figure 2(a) shows an I-V characteristic of the capacitor. The leakage current density of the as-deposited capacitor below 3 V was located below 10^{-7} A/cm^2. The leakage current of $YMnO_3$ films originated from excess oxygen as reported in Ref. [15]. Therefore, annealing in N_2 for 10 min was attempted. As shown in Fig. 2(b), the leakage current density in the low electric field region could be decreased to 2×10^{-9} A/cm^2 by N_2 annealing. In addition, the leakage current density of the capacitor annealed in nitrogen increased after annealing in the oxygen ambient (Figs. 2(c) and 2(d)). This result corresponds well to the fact that the leakage current of $YMnO_3$ films is attributed to excess oxygen.

Figure 3 shows the memory retention characteristics of the $YMnO_3/Y_2O_3/Si$ capacitors with various leakage current changed by annealing. Although the leakage current changed, the saturation of a memory window was observed in the C-V characteristics. The retention time of as-deposited capacitor is about 10^3 s (Fig. 3(a)). The capacitor with lower leakage current shows longer retention time. By annealing in nitrogen ambient, the retention time is prolonged up to over 10^4 s (Fig. 3(b)).

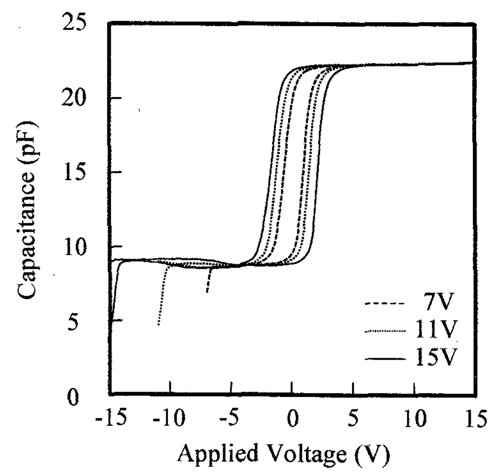

Fig. 1. C-V characteristics of the epitaxial $YMnO_3/Y_2O_3/Si$ capacitor.

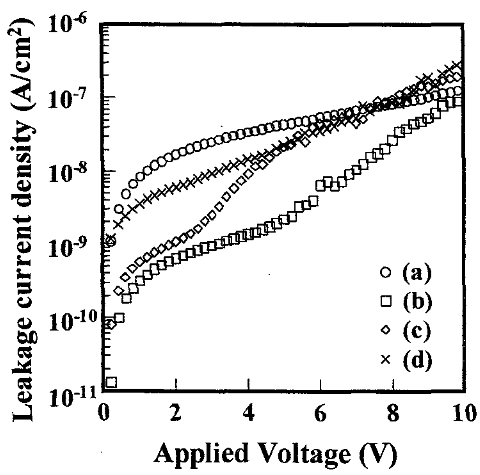

Fig. 2. I-V characteristics of the epitaxial $Pt/YMnO_3/Y_2O_3/Si$ capacitor. (a) as-deposited capacitor, (b) N_2 annealed, (c) O_2 annealed (3 min), and (d) O_2 annealed (6 min).

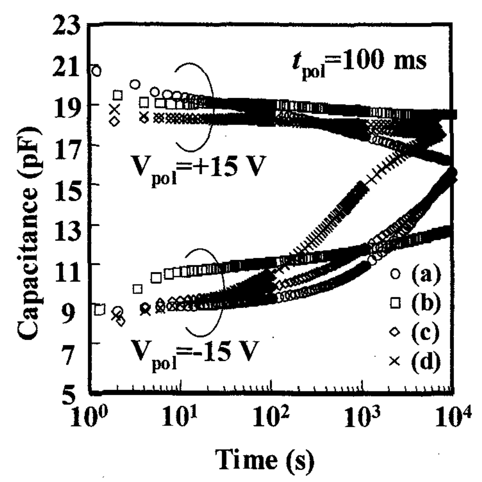

Fig. 3. Memory retention characteristics of the epitaxial $Pt/YMnO_3/Y_2O_3/Si$ capacitor. (a) as-deposited capacitor, (b) N_2 annealed, (c) O_2 annealed (3 min) and (d) O_2 annealed (6 min). Voltage and time for memorizing the status are 15 V and 100 ms, respectively.

As shown in Fig. 2, the change in the leakage current density is obvious in the low-voltage region. In contrast, it does not appear in the high-voltage region. In order to investigate the relationship between the retention characteristics and the leakage current in detail, the I-V characteristics were analyzed using several leakage current mechanisms.[18] Since $YMnO_3$ and Y_2O_3 layers have different dielectric properties, the electric field applied to the each layer must be different. To estimate each electric field, dielectric constants of the $YMnO_3$ and Y_2O_3 layers were assumed as 75 and 10, respectively, based on the capacitance measurement. The dielectric constant of $YMnO_3$ was calculated using not the capacitance measured by the LCR meter but a polarization hysteresis loop, because the actual induced charge at the ferroelectric films surface cannot be calculated by the liner component of dielectric constant. Using the thicknesses of the $YMnO_3$ and Y_2O_3 layers (400 and 20 nm, respectively), the ratio of the electric field applied to the each layer was calculated as 73:27.

Figures 4(i) and 4(ii) show Poole-Frenkel (P-F) plots of the I-V characteristics using the electric field applied to the $YMnO_3$ and Y_2O_3 layers, respectively. In both plots, although the slope of the plots at low electric field are negative, linear relations with positive slope were obtained in the high electric field region. From the equation of P-F emission, J_{PF},

$$\ln(J_{PF}/E) \sim -\frac{qW_t}{kT} + \frac{q\sqrt{q/\pi\varepsilon_i\varepsilon_0}}{kT}\sqrt{E}, \qquad \text{Eq. (1)}$$

where ε_i is the dielectric constant and W_t is barrier height, in the high electric field region, the dielectric constants calculated using the electric field of $YMnO_3$ and Y_2O_3 are 1.2 and 9.1, respectively. The latter is a reasonable value for a dielectric constant of Y_2O_3. Although similar investigation was carried out using the Schottky emission model, the calculated dielectric constants were not reasonable. Therefore, this indicates that the dominant leakage current mechanism of the Pt/$YMnO_3$/Y_2O_3/Si capacitor in the high electric field region is P-F emission from the Y_2O_3 layer. It should be noted that the effect of annealing on the leakage current is small in the high electric field region. It is suggested that annealing affects the electrical properties of $YMnO_3$.

Since small voltage (~1V) is applied to the ferroelectric layer due to the depolarization field, it is important to investigate the leakage current to understand memory retention characteristics. Figure 5 shows log*J* vs log*V* plots of the I-V characteristics. Since the slope of the plot in the low electric field region is nearly 1, the leakage current in low electric field can be explained by ohmic conduction.[18] The effect of annealing on the leakage current is clearly observed in the low electric field region. From the result of the retention characteristics shown in Fig. 2, it is suggested that the ohmic conductance at low voltage is highly related to the retention characteristics and that decreasing the ohmic conductance at low voltage should be effective in prolonging the memory retention time.

Since it is known that the ohmic conductance at low voltage is caused by the charge trapping to the defect in the film, we attempted to evaluate the defect density, which affects the memory retention characteristics. In this study, the pseudo isothermal capacitance transient spectroscopy (ICTS) spectrum was replotted from the retention characteristics. In the case a of normal ICTS spectrum, the instantaneous change of capacitance is measured under the inversion condition of the MIS capacitor to detect the emission from the trap existed in a semiconductor. In contrast, pseudo ICTS spectrum, which is obtained from the retention characteristics of MFIS capacitor, is the change of capacitance for a long period of time (>>1s) without applied bias voltage. In addition, the inversion condition of the MFIS capacitor is maintained not by bias voltage but by the remanent polarization of the ferroelectric layer. Therefore, the pseudo ICTS spectrum should reflect the status of the trap in the ferroelectric layer, because there is a

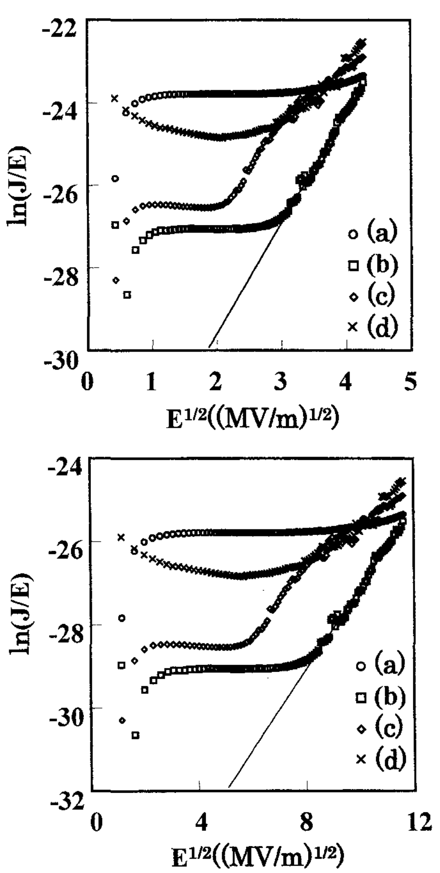

Fig. 4. Schottky plots of the I-V properties using the electric field of (i) $YMnO_3$ and (ii) Y_2O_3 layers. (a) as-deposited $YMnO_3$/Y_2O_3 films, (b) N_2 annealed, (c) O_2 annealed (3 min) and (d) O_2 annealed (6 min).

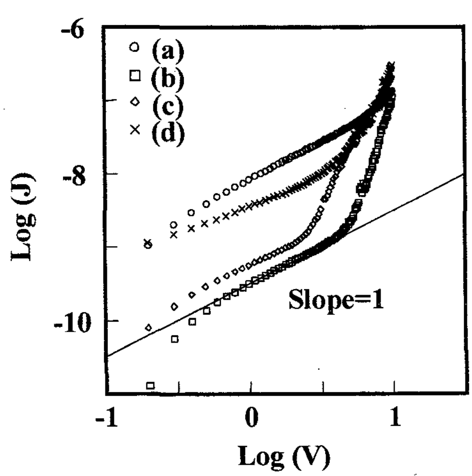

Fig. 5. The log*J* vs log*V* plots for the Pt/$YMnO_3$/Y_2O_3/Si capacitor. (a) as-depo. (b) N_2 annealed (c) O_2 annealed (3 min) (d) O_2 annealed (6 min).

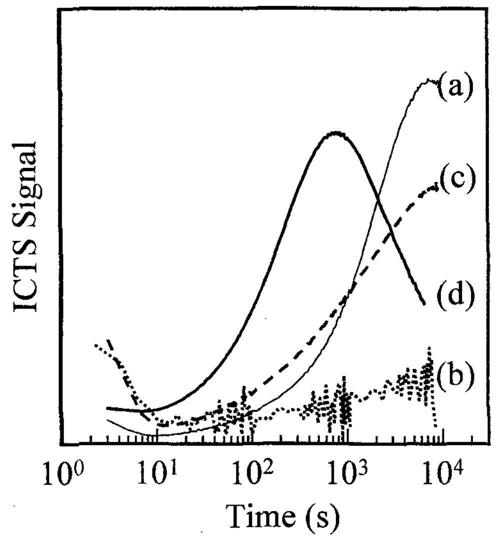

Fig. 6. The pseudo ICTS spectra of (a) as-deposited, (b) N_2 annealed, (c) O_2 annealed (3 min), (d) O_2 annealed (6 min) samples.

relationship between the remanent polarization and the trap. The ICTS signal was derived using the following formula,

$$S(t) = t \cdot dC^2/dt$$
$$= [q\varepsilon_0\varepsilon_s N_T / 2(V_{bi} - V)\tau][t \cdot \exp(-t/\tau)], \qquad \text{Eq. (2)}$$

where $S(t)$ is the ICTS signal. The N_T and τ are trap density and the time constant of the carrier emission, respectively.

Figure 6 shows the pseudo ICTS spectra of the $Pt/YMnO_3/Y_2O_3/Si$ capacitors. A single peak is observed in each spectrum except N_2 annealed sample. It seems that the trap density of the N_2 annealed capacitor is too low to detect a signal in this measurement time. The trap density, N_T, was calculated from the intensity and τ of the peak of the pseudo ICTS spectra. The trap densities of (a) as-deposited, (c) O_2 annealed (3 min) and (d) O_2 annealed (6 min) were in an order of 10^{15} cm^{-3}. The trap density of the $Pt/YMnO_3/Y_2O_3/Si$ capacitor decreases when decreasing the leakage current in low electric field.

From these results, the vanishing mechanism of stored charge in the $Pt/YMnO_3/Y_2O_3/Si$ capacitor can be concluded as follows. The trap existing in the $YMnO_3$ layer underlies the vanishing mechanism and it is also responsible for the relaxation current, which is observed as the leakage current in low electric field. During memory retention, the remanent polarization of the $YMnO_3$ is neutralized by charge trapping introduced by the leakage current. Therefore, the retention time is prolonged by decreasing the leakage current originating from decreasing the trap density of the $YMnO_3$ layer.

CONCLUSION

The relationship between the leakage current and memory retention characteristics of $Pt/YMnO_3/Y_2O_3/Si$ capacitors was investigated. It was found that the leakage current of $Pt/YMnO_3/Y_2O_3/Si$ capacitors could be decreased by annealing in nitrogen. The retention time was prolonged from 10^3 to 10^4 s by the annealing in nitrogen. From the analysis of the leakage current, it was revealed that in high electric field, Poole-Frenkel emission from Y_2O_3 layer was the dominant leakage mechanism. On the other hand, the dominant leakage current in low electric field, which has a strong relationship with retention time, was ohmic conduction. Since the ohmic conductivity was related to the number of defects obtained from the pseudo ICTS spectra, it is suggested that the reduction of defects is important to improve the retention characteristics.

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