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Studies on Improving Retention Time of Memorized State of MFIS Structure for Ferroelectric Gate FET Memory

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1. Introduction

There exists a great interest in the Metal-Ferroelectric-Insulator-Semiconductor (MFIS) FET as a nonvolatile memory device. The FET-type memory is more feasible due to its non-destructive readout capability and compliance with the scaling rule, than the storage capacitor-type. However, the MFIS FET has difficulties in realizing sufficiently long retention time of memorized state. It is mainly because of depolarization field which intrinsically exists in the stacked-gate structures.

In this study, we have analyzed the retention characteristics regarding the effect of leakage current in the ferroelectric and the insulator layers by our newly developed simulation.

2. Analysis

Band diagrams of an MFIS structure with no bias voltage are shown in Fig.1. Even when bias voltage is not applied to the MFIS structure, electric field exists in the ferroelectric and the insulator layers. Therefore, current flows through the ferroelectric and the insulator films under the electric field. In order to investigate the origin of the retention characteristics of MFIS structure, we derived equations(1)-(4) as follows,

$$D = \varepsilon_0 \varepsilon_f E_f + P_d, \quad (1)$$

$$E_f = \frac{-P_d - Q_{inj} - Q_{Si}}{\varepsilon_0 \varepsilon_f}, \quad E_i = \frac{-Q_{Si}}{\varepsilon_0 \varepsilon_f}, \quad (2)$$

$$E_f d_f + E_i d_i + V_{Si} + V_{fb} = V_g, \quad (3)$$

$$-\frac{dQ_{inj}}{dt} = J_f(E_f) - J_i(E_i), \quad (4)$$

where D : electric displacement in the ferroelectric layer, E_f: electric field in the ferroelectric, ε_0: permittivity of free space, P_d: contribution to the polarization due to switching dipoles and simulated by Miller's equation[1], Q_{inj}: injected charge density into the interfacial region of the ferroelectric and the insulator, Q_{Si}: surface charge density of the semiconductor, ε_i: dielectric constant of the insulator, V_g: voltage applied to the MFIS, d_f and d_i: thicknesses of the ferroelectric and the insulator, V_{Si}: surface potential of the semiconductor, V_{fb}: flat-band voltage, J_f and J_i : leakage current densities in the ferroelectric and the insulator, respectively.

J-V and *J-t* characteristics of a real Al/$SrBi_2Ta_2O_9$(SBT)/Pt capacitor have been studied to make a model of leakage current characteristics of ferroelectric thin film. Figure 2(a) shows a *J vs.* $E^{1/2}$ plot of the measured *J-V* characteristics. The leakage current is limited by schottky barrier in the low field region. In addition, *J-V* characteristics in the high field region is simulated well by Fowler-Nordheim (F-N) conduction. The calculated *J-V* curve of sum of schottky and F-N currents agrees well with measured data shown in Fig. 2(b). On the other hand, *J-t* plot of a dielectric film obeys

$$J_f = J_0 t^{-\beta}, \quad (5)$$

where β of 0.52 was experimentally obtained in the film. So, the current density can be simulated by the product of modeled curve of Fig.2(a) and Eq. (5).

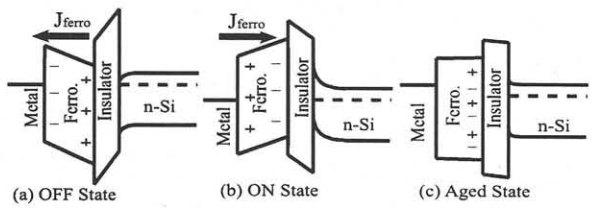

Fig.1 Band diagram of a MFIS structure in (a)OFF state, (b)ON state and (c)Aged state, respectively.

3. Results and Discussion

The MFIS structure is polarized on write operation and then is short-circuited on hold operation. Initial state of the hold operation have to be determined to simulate retention charac-

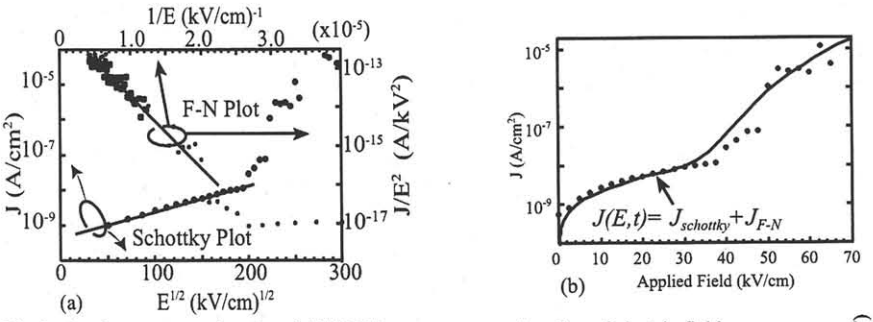

Fig.2 Leakage current density of Al/SBT/Pt structure as a function of electric field. (a) Plot based on Schottky conduction and F-N tunneling models. (b) Experimental data and calculated curve of the current density.

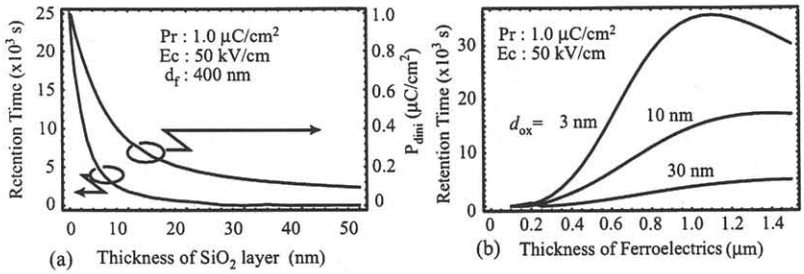

Fig.4 Calculated retention time *vs*. Film thickness of (a) the SiO_2 and (b) the ferroelectric layer.

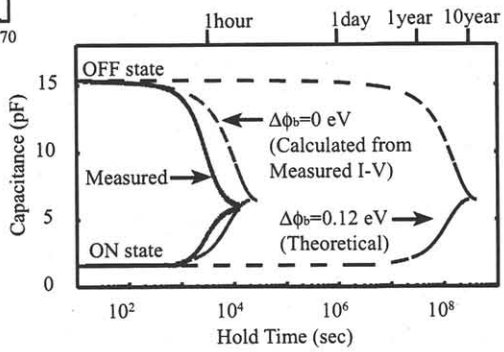

Fig.3 Measured (solid curve) retention characteristic of Al/SBT/SiO_2/Si structure compared with the calculated (dashed curves) ones for $\Delta\phi_b$ =0eV and $\Delta\phi_b$ =0.12eV .

teristics. If J_f and Q_{inj} are assumed to be 0 initially, the state of the MFIS structure is determined definitely by V_g and P_d. So the initial state of the hold operation is determined by the initial ferroelectric polarization(P_{dini}), which is a value of P_d right after the write operation.

Ageing effect of ON and OFF capacitances has calculated by solving Eqs.(1)-(5) for Al/SBT/SiO_2/Si structure. The calculated capacitances are drawn by a dashed line for $\Delta\phi_b$=0 eV , and agreed well with the measured data (solid line) [2]. This agreement supports the validity of our model. Retention time is defined as the time when the capacitance difference between ON and OFF state decays to a half of the initial value(Fig.3).

Figure 4(a) shows d_{ox} dependence of retention time and P_{dini} at V_{fb}-V_g of -0.35 V. Retention time drastically increases as the d_{ox} decreases. There are mainly two reasons to explain this phenomenon. One is the increase of P_{dini} and the other is decrease of J_f at the hold state. P_{dini} increases with decreasing d_{ox} as shown in Fig.4(a). The increase of retention time is induced by increase of E_f at the write operation and decrease of E_f at the hold operation. However, dependence of the P_{dini} decreases with d_{ox} more slowly than retention time. This fact indicates that decrease of J_f effectively affects the increase of the retention time.

On the other hand, when d_{ox} is reduced, electric field in the SiO_2 layer at the hold state increases. However, this field at the initial hold state is only 1.73 MV/cm, even if d_{ox} is 1 nm. Therefore, we can neglect tunneling current though SiO_2 layer.

Figure 4(b) shows d_f dependence of retention time for different thicknesses of SiO_2. As d_f increases, E_f at both write and hold operations decrease. Therefore, there exists an optimum value of d_f. The optimum d_f increases with increasing d_{ox}. Actually, the optimum d_f is 1.1 μm even when d_{ox} is as thin as 3nm.

In order to improve the retention characteristics of MFIS structures, we focused on the effect of an increase of barrier height between the metal and the ferroelectric ($\Delta\phi_b$). The parameter ϕ_b was obtained from experimental data. Figure 3 also suggests that the larger $\Delta\phi_b$ is quite effective to improve the retention time. The calculation shows that $\Delta\phi_b$=0.12 eV is required to realize several years of the retention time.

4. Conclusion

The retention characteristics for MFIS structures have been examined using our new simulation method which considers leakage current through the ferroelectric and the insulator layers. The calculated curves agree well with the experimental data. We found that the barrier height between the top electrode metal and the ferroelectric film is quite essential to control the retention time. Therefore, an increase in the barrier height is very effective to improve the retention time.

References

[1] S. L. Miller and P. J. McWhorter: J. Appl. Phys. **72**, 5999 (1992)
[2] M. Okuyama, H. Sugiyama, T. Nakaiso, and M. Noda: Abstracts of ISIF 2000, p.153