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Impact of Zr Concentration on Time-Dependent Dielectric Breakdown of HfZrO-based Ferroelectric Tunnel Junction (FTJ) Memory

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Abstract

We systematically investigated the impact of Zr concentration on time-dependent dielectric breakdown (TDDB) of HfZrO-based ferroelectric tunnel junction (FTJ) memory. The time-to-breakdown (T_{bd}) becomes shorter with increasing Zr concentration. One plausible mechanism is that the HfZrO capacitance becomes higher as Zr concentration increases, and thus voltage applied to the interfacial layer SiO_2 becomes higher, which accelerates the defect generation and leads to shorter T_{bd}. A reliable FTJ with long T_{bd} and high ON/OFF ratio was demonstrated by controlling HfZrO deposition temperature and Zr concentration.

1. Introduction

HfO_2 based ferroelectric materials and related devices such as FeFET, FeRAM and FTJ are attracting much attention for next generation memory applications. Among them, we have demonstrated HfO_2 based FTJs with characteristics desirable for both high-density low-cost applications and AI applications; low operation current, rectifying property, and analog switching [1-5]. In addition, 2-terminal structure is suitable for cross-point architecture. Although the FTJ shows excellent memory performance, stress induced breakdown during program/erase cycling is one of the critical issues [6-7]. To realize highly reliable FTJ, it is necessary to understand the failure mechanisms and establish a guideline for time-to-breakdown (T_{bd}) improvement. In this work, we systematically investigated the impact of Zr concentration on the T_{bd} of HfZrO-based FTJs, and demonstrated the improvement of both T_{bd} and ON/OFF ratio by optimization of the HfZrO deposition process.

2. Impact of Zr concentration on T_{bd}

Fig.1 shows the device structure of the FTJ. A ferroelectric HfZrO layer (FE-HfZrO) and a paraelectric SiO_2 interfacial layer (IL-SiO_2) are sandwiched between top electrode (TE) and bottom electrode (BE). Fig.2 shows I-V characteristics of the FTJs. Polarization reversal in the HfZrO causes ON/OFF switching.

We carried out TDDB measurements for 3 types of devices with different Zr concentration in the HfZrO. We used DC stress for the TDDB measurements (Fig.3(a)), and monitored current across the stack until breakdown occurs (Fig.3(b)). Fig.4 shows Weibull distribution of T_{bd} of the FTJs under (a) positive stress of 4.4V and (b) negative stress of -5.1V. Each T_{bd} distribution normalized by the device size is located on a single curve. This result suggests that the percolation model, which is well-known to explain the conventional oxide breakdown, is applicable to the FTJ failure.

As shown in Fig.4, the average T_{bd} for both polarity become shorter with higher Zr concentration (x_{zr}). On the other hand, the Weibull slope βs do not depend on the x_{zr}. According to the percolation model, Weibull distribution of T_{bd} is described by the following equation [8],

$$\ln(-\ln(1-\mathrm{F})) = \beta \cdot \ln(\lambda(t)) + \ln(N) = \frac{t_{ox}}{a_0} \cdot B \cdot \ln(T_{bd}) + \frac{t_{ox}}{a_0} \cdot \ln(k) + \ln\left(\frac{A_0}{a_0^2}\right) \quad (1)$$

where a_0 is defect size, B is time-exponent of defect generation rate, k is proportionality factor of the defect generation rate, and A_0 is device area, respectively. Here, we assumed t_{ox} corresponds to the thickness of the IL-SiO_2, since our previous work revealed that the defects generation in the IL-SiO_2 triggers the breakdown of the FTJ [7]. Since the Weibull βs for the FTJs in Fig.4 show the same value irrespective of the Zr concentration (x_{zr}), t_{ox}, a_0 and B for the FTJs do not change with x_{zr}. Hence, shorter T_{bd} in higher x_{zr} might be caused by increase in the k in the equation (1). In the previous work, we confirmed that the k, that is, acceleration factor of the defect generation is increased by stress voltage [6-7]. Therefore, the T_{bd} degradation for higher x_{zr} is presumably due to higher electric field across the IL-SiO_2 which accelerates the defect generation.

We found that the initial leakage current ($I_{initial}$) before applying stress voltage increases for the FTJ with high x_{zr} (Fig.5). Since the tunneling current across the FTJ stack is determined by the electric field to the IL-SiO_2 (E_{SiO2}), higher $I_{initial}$ for high x_{zr} also suggests that the E_{SiO2} is increased with increasing the x_{zr}. One plausible mechanism is that the HfZrO capacitance becomes higher with x_{zr}, therefore the voltage applied to the IL-SiO_2 becomes higher, which results in shorter T_{bd} as shown in Fig.6. Fig.7 shows that T_{bd} decreases with increasing $I_{initial}$. From Figs.4 and 5, we can understand that both $I_{initial}$ increase and T_{bd} degradation observed for the FTJ with high x_{zr} derive from E_{SiO2} increase and enhanced defect generation. As a result, reduction of the E_{SiO2} is necessary to ensure long T_{bd}.

3. Demonstration of longer T_{bd} and high ON/OFF ratio

To reduce the E_{SiO2} and enhance tolerance to breakdown, high temperature deposition of the HfZrO is found to be an effective solution (Fig.8). However, increase in the deposition temperature degrades ON/OFF ratio (Fig.9). Therefore, there is a trade-off between T_{bd} and ON/OFF ratio.

To overcome the trade-off, we further investigated material properties for the FE-HfZrO layers deposited at a high temperature. Fig.10 shows dependence of remnant polarization (P_r) on Zr concentration (x_{zr}) for high temperature FE-HfZrO. There is an optimal x_{zr} to maximize P_r. In general, P_r corresponds to ON/OFF ratio [9]. Therefore, Zr optimization could compensate the ON/OFF degradation, and thus improves the trade-off. To demonstrate high ON/OFF ratio for the FTJ with high temperature HfZrO, we designed x_{zr} based on Fig.10. Fig.11 shows ON/OFF ratio vs $I_{initial}$ for the FTJ with high temperature HfZrO deposition. Simultaneous achievement of low leakage current and high ON/OFF ratio is demonstrated by the x_{zr} control. We also confirmed that the T_{bd} is improved for the optimized FTJ with low leakage current and high ON/OFF ratio as shown in Fig.12(a)(b), indicating E_{SiO2} is reduced by Zr optimization. Optimization of HfZrO deposition temperature and Zr concentration is a key to realize highly reliable FTJ.

4. Conclusions

We revealed that the suppression of defect generation by reducing the electric field applied to IL-SiO_2 is a solution to improve the reliability of the FTJ. The simultaneous improvement of the T_{bd} and the ON/OFF ratio was achieved by optimization of HfZrO deposition temperature and Zr concentration. Considering the advantages such as low operation current, rectifying property, and analog switching, the HfO_2-based FTJ has high potential for various emerging memory applications.

References

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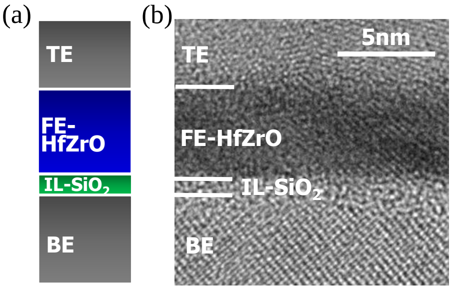

Fig.1 Device structure of HfZrO FTJ. (a) Schematics and (b) cross-sectional TEM.

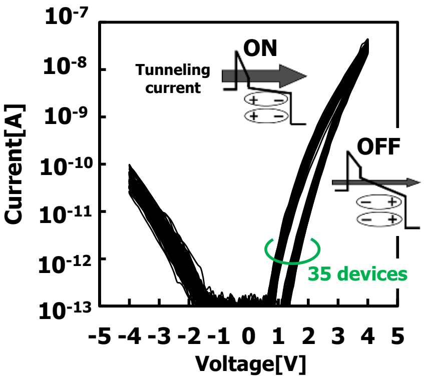

Fig.2 I-V characteristics of the FTJs.

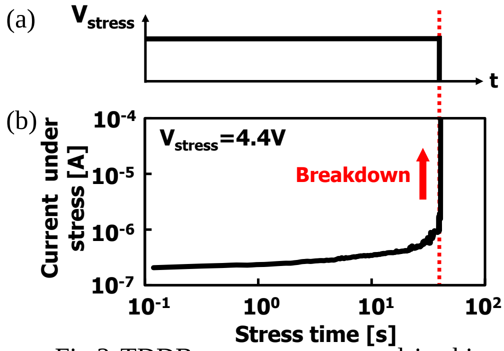

Fig.3 TDDB measurement used in this study. (a) Measurement sequence. (b) Current-time trace until breakdown.

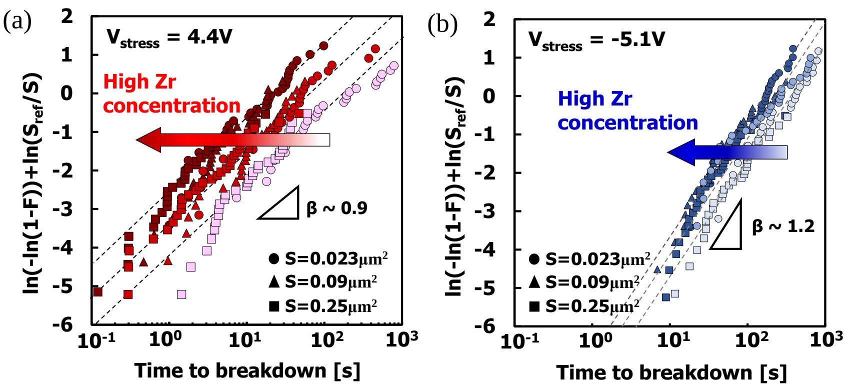

Fig.4 Weibull distribution of time-to-breakdown (T_{bd}) of FTJs under (a) positive stress of 4.4V and (b) negative stress of -5.1V.

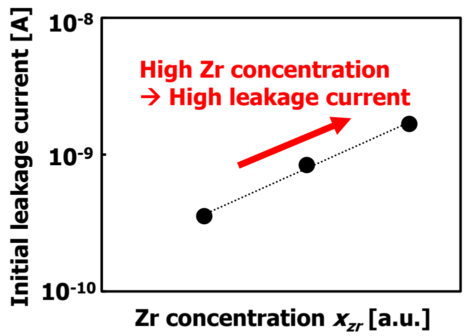

Fig.5 Relation between Zr concentration (x_{zr}) and initial leakage current ($I_{initial}$).

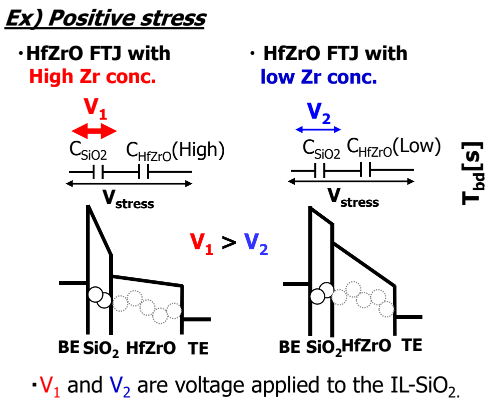

Fig.6 Breakdown model of HfZrO FTJ. High HfZrO capacitance accelerates defects generation in IL-SiO_2 because higher voltage is applied to IL-SiO_2.

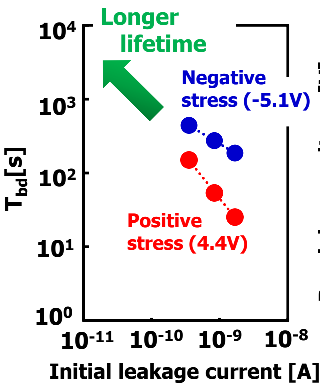

Fig.7 Relation between initial leakage current and time-to-breakdown (T_{bd}) .

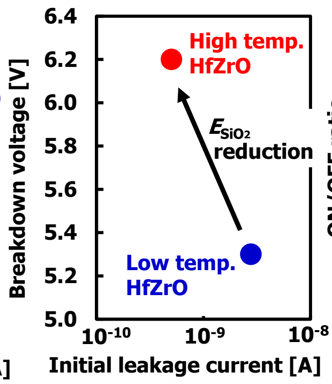

Fig.8 Dependence of initial leakage current and breakdown voltage on HfZrO deposition temperature.

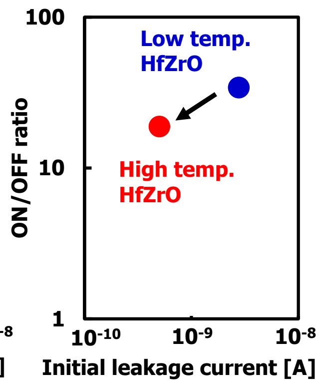

Fig.9 Dependence of initial leakage current and ON/OFF ratio on HfZrO deposition temperature.

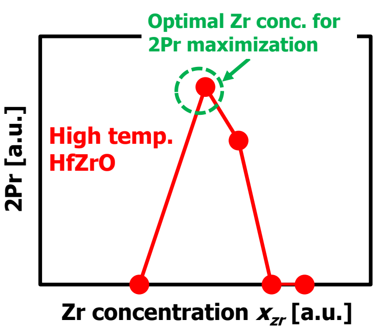

Fig.10 Dependence of remnant polarization (Pr) on Zr concentration (x_{zr}) for high temperature FE-HfZrO.

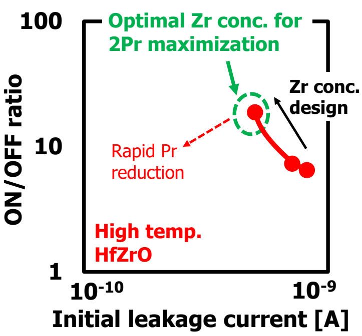

Fig.11 ON/OFF ratio vs initial leakage current for the FTJ with high temperature HfZrO.

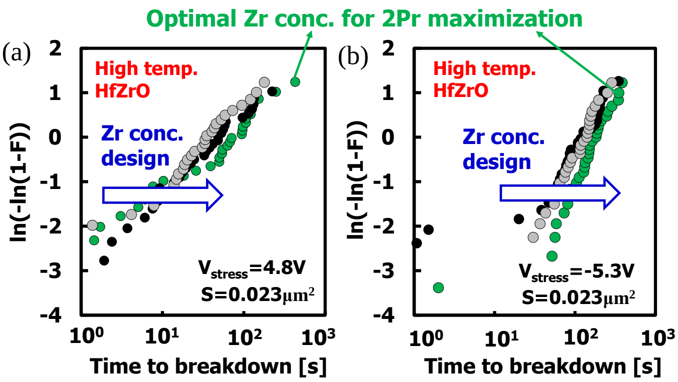

Fig.12 Demonstration of time-to-breakdown (T_{bd}) improvement by optimization of HfZrO deposition temperature and Zr concentration. (a) Positive stress. (b) Negative stress.