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Effect of Self-heating on TDDB in Ultra-thin MgO Magnetic Tunnel Junctions for Spin MRAM

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1. Introduction

Magnetoresistive Random Access Memory (MRAM) is a promising device for high-density (over Gbit-scale), high-speed (equal to DRAM or better) non-volatile RAM, and much research has been done over several years with a view to overcoming the problems regarding its practical use [1][2]. Spin Torque Transfer switching MRAM (Spin-MRAM) is considered to be the most promising candidate and there are some papers on this new device [3][4]. MgO is expected to be the best material for magnetic tunnel junction (MTJ) of Spin-MRAM, because MgO-MTJ is known to enhance spin polarization by the coherent tunneling effect [5], resulting in large MR (Magnetoresistance) and decrease of writing current for the MTJ switching [6][7]. MgO-MTJ has been shown to be an excellent barrier with little resistance drift compared with MTJ using alumina [8][9]. Notwithstanding its excellent potential, the breakdown mechanism of MgO-MTJ has not been well understood although a thorough understanding is essential for commercialization of Spin-MRAM. In this paper, we demonstrate for the first time the modeling of dielectric breakdown phenomena of MgO-MTJ by TDDB (Time-Dependent Dielectric Breakdown) measurement concerning the effect of self-heating using simulation and conclude that E-model with the effect of self-heating at MgO-MTJ during current stress (power) removed gives the best fitting as a degradation model of MgO-MTJ ultra-thin dielectrics.

2. Thermal Simulations and Experimental Results

To our knowledge, there are three popular lifetime prediction models for thin dielectrics. Among them, the electric-field acceleration model (E-model) is one of the classical models describing the relationship between stress and TDDB lifetime of dielectrics in which logarithmic of mean time to failure (*TF*) is proportional to external electric field as shown in equation (1).

$$\ln(TF) = \frac{\Delta H_0}{K_B T} - \gamma \cdot E \tag{1}$$

in which, ΔH_0 is activation energy, K_B is Boltzmann constant, T is temperature, γ is field acceleration factor, and E is applied electric field. This model gives good approximation under low electric field [10]. On the other hand, some researchers suggest that the breakdown process is current-driven and TF should show a 1/E dependence (1/E-model) in which total charge of injected hole (Q_h) due to Fowler-Nordheim (FN) current is critical to final breakdown process [11]. Recently, the power-law model (V-model) has been proposed that gives good approximation for ultra-thin dielectric films in which electrons injected through the direct tunneling (D-T) process can cause damage in the dielectrics depending on the applied voltage [12].

At first, we failed to fit our TDDB results of MgO-MTJ using conventional degradation models because we encountered a problem in applying them to our devices, namely, the stress current density for a spin-injection device was extremely high ($J_C \sim 10^6$A/cm^2) compared with conventional CMOS stress conditions as shown in Table I, and therefore we found the necessity of regarding the effect of temperature increase attributable to stress power, similar to the previous report [15].

TABLE I Comparison of TDDB Test Results

Reference	Dielectric material	Thickness [nm]	Stress Volt. [V]	Current Dens. [A/cm^2]	TBD [sec]	Temperature [˚C]
Chen et al. [11]	SiO_2 (NFET)	13	16.5	$1*10^{-2}$	$3*10^{2}$	R. T.
Takayanagi et al. [13]	SiO_2 (NFET)	2.5	2.4	$1*10^{-1}$	$1*10^{4}$	27
Ohgata et al. [14]	SiO_2 (NFET)	1.6	2.7	$1*10^{0}$	$1*10^{4}$	125
This Work	MgO (MTJ)	1.25	1.1	$2*10^{6}$	$1*10^{5}$	25

To find the accurate degradation model of ultra-thin MgO-MTJ regarding the effect of temperature, three-dimensional thermal simulations of MgO-MTJ system were done using a finite element method with boundary conditions to solve the heat equation

$$c_p d \frac{\partial T}{\partial t} = \kappa \nabla^2 T + Q \tag{2}$$

in which the symbols have the following correspondence: C_p heat capacity, *d* mass density, *T* temperature, *t* time, κ heat conductivity, *Q* heat generation at MgO. It is assumed that there is side-wall heat diffusion from each layer to SiO_2 environment and temperature is fixed at the substrate (not shown in Fig. 1) and heat is produced only at MgO depending on the value of injected current density and *RA* (resistance area product) of MTJ. Fig.1 shows the simplified MRAM cell structure including MTJ and Table II shows the parameters used in the numerical simulations. Examples of temperature increase at MgO using our TDDB stress conditions and their dynamic behaviors are shown in Fig. 2 (a) and (b), respectively. Temperature increase is between 40 to 200 degrees depending on injected power and they saturates in the time scale of a few micro seconds.

TABLE II Parameters used in the thermal simulations

Layer Name	Element	Elec. Cond. [1/(Ω·m)]	Therm. Cond. [W/(m·K)]	Mass Density [kg/m^3]	Heat Capacity [J/(kg·K)]
Environment	SiO_2		1.9	2200	745
Via Plug	W	1.89E+07	174	19250	130
Base / Plug	Ta	7.61E+06	58	16600	142
Wire (Bit-Line)	Al	3.77E+07	237	2700	900

As a next step, we fabricated MTJ samples and tried TDDB test of each sample. Fabrication process and techniques for measuring the electrical and magnetic degradation of MTJ simultaneously are shown in our previous reports [9][16]. Accurate MgO thickness of our test samples was measured using transmission electron microscopy (TEM) to calculate the correct value of electric field at each stress condition. We stressed over 40bits at each stress condition, and we tried four different bias conditions for each TDDB test to get accurate lifetime by extrapolation. Fig. 3 shows examples of Weibull plots of the same wafer measured by four stress bias conditions and each data showed good linearity on this scale. Using the thermal simulations, we calculated the temperature increase ΔT of MTJ during each stress condition using the equation

$$\ln(TF_{\mathrm{mod}}) - \ln(TF_{meas}) = \Delta H_0 \times \left(\frac{1}{K_B T_1} - \frac{1}{K_B T_2} \right) \tag{3}$$

in which the symbols have the following correspondence: TF_{meas} actual measured lifetime, TF_{mod} measured lifetime with effects of temperature increase (ΔT) due to self-heating removed, T_1=298 [K], T_2=298+ΔT [K], ΔH_0 activation energy and we used the value 0.8eV derived from our thick MgO-MTJ samples. Fig. 4 shows TF vs. Vox in semi-log scales for (a) and (b) as references, and TF vs. Eox in semi-log scales for (c) and (d) to check the consistency with E-model [10], TF vs. Vox in log-log scales for (e) and (f) to check the consistency with V-model [12]. We have removed the effects of temperature increase (ΔT) due to self-heating using equation (3) from the actual measured data at 25 ˚C in (a), (c), (e) to create the graphs in (b), (d), (f), respectively. We have also checked the consistency with 1/E-model [11] using same procedures (not shown in Fig. 4). Among these results, data shows best fitting in Fig. 4 (d) in which not only slopes of samples with different thickness are almost equal to each other but also TF plots are almost on a unique line.

3. Discussion and Conclusions

Based on these results, we concluded that E-model with the effect of self-heating at MgO-MTJ during current stress (power) removed gives the best fitting as a degradation model of MgO-MTJ ultra-thin dielectrics. We think that the degradation process of MgO-MTJ might be caused mainly by local electric field that tends to weaken polar molecular-bonds between atoms, thereby lowering the enthalpy of activation required for bond breakage by standard Boltzmann processes [17]. We still don't deny the possibility of the combination of percolation mechanism with E-model as a degradation model of MgO-MTJ because polar molecular-bonds between atoms weakened by local electric field can lower the threshold of stress capable of making traps which finally create the percolation paths through the dielectrics.

In conclusion, we suggest that the self-heating during current stress plays an important role for the degradation process of ultra-thin MgO-MTJ of Spin-MRAM, and we have concluded that E-model with the effect of self-heating removed gives the best fitting. This result also supports good scalability of ultra-thin MgO-MTJ for future spin-injection devices for which good reliability can be expected by reducing injected current through scaling of applied voltage and MTJ size. Our thermal simulation results also support better lifetime by pulse stress shorter than 1 micro-seconds.

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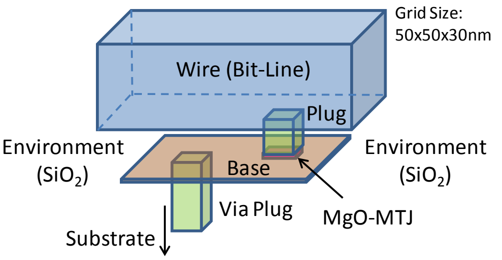

Fig. 1 Simplified MgO-MTJ structure employed for three-dimensional thermal simulations using a finite element method with boundary conditions to solve the heat equation (2) to find the accurate degradation model of ultra-thin MgO-MTJ regarding the effect of temperature.

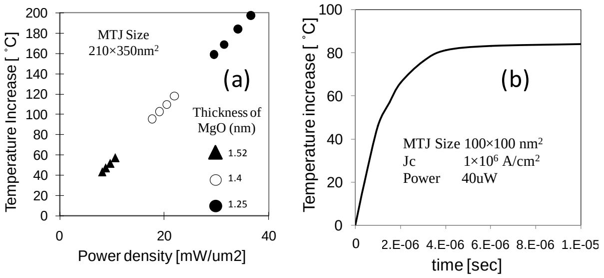

Fig. 2 (a) Example of temperature increase at MgO using our TDDB stress conditions, and (b) their dynamic behaviors, respectively. Temperature increase is between 40 to 200 degrees depending on injected power and saturates in the time scale of a few micro seconds.

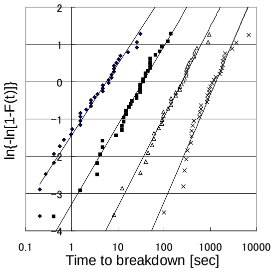

Fig. 3 Examples of Weibull plots of TDDB test results at 25℃. Each data shows good linearity in Weibull plots. Test conditions are anti-parallel status and negative bias direction.

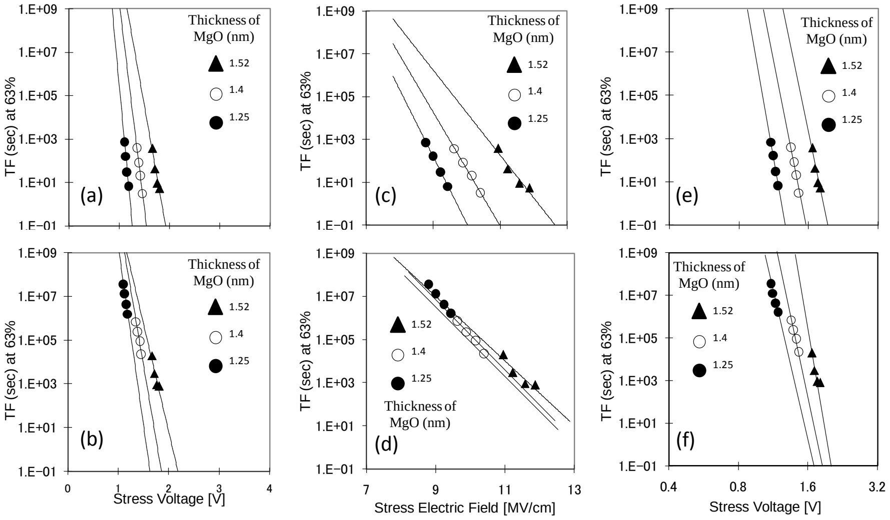

Fig. 4 TF vs. Vox in semi-log scales for (a) and (b) as references, and TF vs. Eox in semi-log scales for (c) and (d) to check the consistency with E-model [10], TF vs. Vox in log-log scales for (e) and (f) to check the consistency with V-model [12]. We have removed the effects of temperature increase (ΔT) due to self-heating using equation (3) from the actual measured data at 25 ˚C in (a), (c), (e) to create the graphs in (b), (d), (f), respectively. Among these results, data shows best fitting in Fig. 4 (d) in which not only slopes of samples with different thickness are almost equal to each other but also TF plots are almost on a unique line. MTJ status under test condition is anti-parallel and stress is applied in negative bias polarity at 25℃ [9]. Accurate MgO thickness of our test sample was measured using transmission electron microscopy (TEM) to calculate the correct value of electric field at each stress condition.