A Physics-Based Statistical Model for Reliability of STT-MRAM Considering Oxide Variability

Chih-Hsiang Ho, Georgios D. Panagopoulos, Soo Youn Kim, Yusung Kim, Dongsoo Lee and Kaushik Roy
Purdue University, West Lafayette, IN 47906, USA

Abstract– A physics-based statistical model considering oxide thickness (T_{ox}) variability is proposed for evaluating the impact of time-dependent dielectric breakdown (TDDB) on the performance of spin-transfer torque magneto-resistive random access memory (STT-MRAM). The statistics of breakdown events are captured by the percolation theory, physics-based analytical model for successive break down (BD) and 1-D non-equilibrium Green's function (NEGF). Using the proposed model, we examine T_{ox}-dependence of STT-MRAM performance distribution, such as tunneling magneto-resistance ratio (TMR) and critical current (I_C). Simulation results clearly show that oxide variability needs to be taken into account for better lifetime prediction. The proposed model has been validated with experimental data.

I. INTRODUCTION

Spin-transfer torque magnetoresistive random access memory (STT-MRAM) is recognized as a promising candidate for future embedded memories because of its non-volatility, superior scalability and compatibility with CMOS technologies. However, the performance of STT-MRAM is sensitive to the tunneling oxide thickness and, hence, any variations in the oxide thickness can have a large impact on the bit-cell performance. Furthermore, one of the primary reliability concerns of STT-MRAM, time-dependent dielectric breakdown (TDDB), as illustrated in Fig. 1, also strongly depends on the oxide thickness [1-3]. To design robust STT-MRAMs, there is a need for an accurate model which is capable of capturing the impact of oxide thickness variation on both the statistics of "initial" (at time "0") performance and TDDB-induced degradation in a common framework. The existing simulation methodologies either focus on modeling initial performance [4-7] or assume uniform dielectric thickness [8-9] leading to inaccurate predictions. In this work, we propose a physics-based statistical model to evaluate TDDB effect on STT-MRAM considering the impact of oxide thickness variation. Using the proposed model, we explore in detail the time-dependent performance of MTJ with different oxide thickness variation. The model has been validated with experimental data [10-11].

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II. STATISTICAL MODELING & CHARACTERIZATION FOR BDs

To capture the statistics of first BD time, we apply percolation model. Based on percolation model, TDDB degrades MTJ by inducing breakdown (BD) paths during stress which connects the electrodes in the two sides of dielectric. The induced statistical degradation can be attributed to the random BD time for the first and successive BD events [12-13]. Hence, to accurately predict the time-dependent performance of STT-MRAM, the statistics of the first and successive BD time need to be properly modeled. Assuming circular shape of trap, our algorithm continues generating traps in oxide until a BD path is formed. The probability of trap generation follows a power-law with time [13-14].

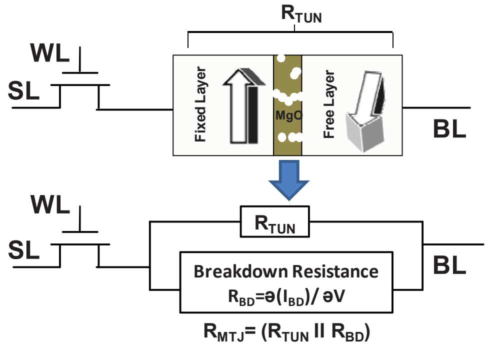

Fig. 1: Schematic of 1T-1MTJ memory cell with a breakdown path in oxide. A breakdown resistance, $R_{BD,}$ is added in parallel to MTJ after a breakdown path is formed.

$$p = kt^a \qquad (1)$$

where a is the power-law exponent of trap generation, k is the parameter that depends on the stress conditions [2, 14].

$$k = \frac{\left(\frac{q t_{MgO} N_{BD}}{J_{MTJ}\gamma}\right)^{-a}}{\Delta t}\left(\frac{A_{MTJ}}{a_0^2}\right)^{-a_0/T_{MgO}} \qquad (2)$$

where a_0 is the trap diameter, A_{MTJ} is MTJ area, T_{MgO} is the oxide thickness, V_{MTJ} is the voltage across MTJ, γ is the trap generation efficiency and N_{BD} is the critical trap density [15].

$$N_{BD} = \frac{t_{MgO}}{a_0^3} exp\left(\frac{-a_0}{t_{MgO}} log\left(\frac{A_{MTJ}}{a_0^2}\right)\right) \qquad (3)$$

Once the traps in the oxide connect the two electrodes, the time is extracted as the first BD time. Having the first BD time distribution, we can evaluate the distribution of successive BD events by the percolation based analytical model [16].

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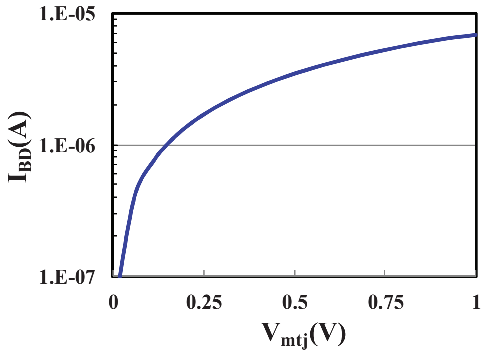

Fig. 2: characteristics of breakdown path evaluated using 1-D NEGF.

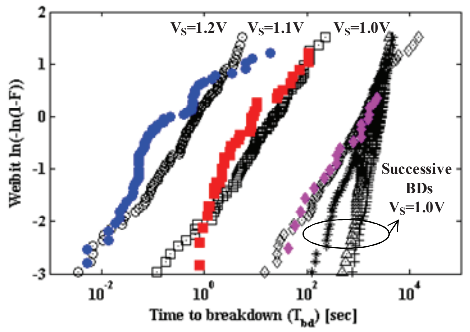

Fig. 3: Weibull distribution for V_{STRESS} =1.0V, 1.1V and 1.2V. The distribution for successive BD events (2nd, 3th and 4th BD) are also shown for V_{STRESS} =1V case. (Filled markers: measured results [10]; open markers: simulated results)

$$W_{kBD} = k\beta ln\left(\frac{T_{BD}}{T_{BD63\%}}\right) - \ln(k!) \qquad (4)$$

where β is the slope of first BD distribution in Weibull plot and $T_{BD63\%}$ is the mean time to first BD. The post-BD current is obtained using 1-D non-equilibrium Green's function (NEGF) [17] which is a common framework for evaluating quantum transport in nano-scale devices. Since the BD path is considered to be a narrow constriction, the resulting quantized energy levels change with the thickness of BD path and hence appear as potential barrier in the BD path for the passing electrons. Assuming the minimum constriction of the BD path (t_{BD}) is the trap size, the maximum potential barrier height of BD path is given by [18]

$$\Phi_{BD} = \frac{\pi^2 h^2}{2qmt_{BD}} \qquad (5)$$

The obtained Φ_{BD} is then fed into 1-D NEGF for evaluating the I-V characteristics of the BD path, as shown in Fig. 2. Finally, in circuit simulation, the BD paths are described by a voltage controlled current source which connects in parallel with MTJ, as shown in Fig.1. The MTJ performance is evaluated by self-consistent Landau-Lifshitz-Gilbert (LLG) NEGF simulation model with the parameters listed in Table 1 [4].

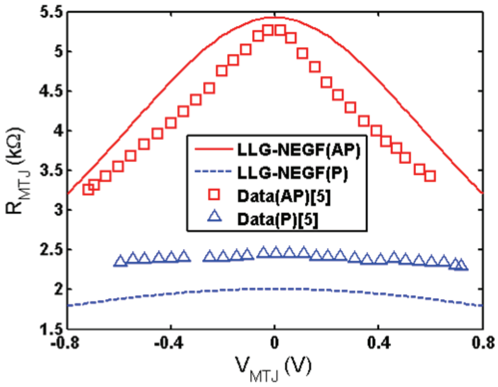

Fig. 4: The comparison of resistance of MTJ in parallel (P) and anti-parallel (AP) states from our simulations and experimental data [11] at T_{OX}=1.15nm.

Table 1. STT-MRAM parameters used in the proposed model

Parameters	Value
Energy Barrier(E_a)	$56k_BT$ at T=300K
Gilbert Damping, α	0.014
Saturation Magnetization (M_S)	860 kA/m
Spin Torque Parameters (P_{PL}, P_{FL}, γ_{PL}, $\gamma_{\_FL}$)	0.4441, 0.4441, 1.182, 1.182
Free Layer Dimensions	60nm x60nm x1.5nm
Fermi level for FL & PL	2.25eV(FL), 2.25eV(PL)
MgO thickness	1nm

III. SIMULATION RESULTS AND DISCUSSIONS

The applied parameters for the proposed model are first validated in Fig. 3-4. Fig. 3 shows the matching results of the time to breakdown for different stress voltages (V_{stress}=1.0V, 1.1V, 1.2V) with experimental data [10]. The statistics for successive BD events are also shown for V_{STRESS}=1V case. It is worthy to note that a small difference of stress voltage causes large difference in BD time. Fig. 4 compares the MTJ resistance in parallel and anti-parallel states with experimental results [11].

Fig. 5 illustrates the effect of oxide thickness on the mean time to BD ($T_{BD63\%}$) and the spread of distribution (β: Weibull slope). It is evident that both $T_{BD63\%}$ and β decrease with decreasing oxide thickness which indicates larger spread and shorter BD time as oxide thickness decreases. The results validate that the lifetime of STT-MRAM will be significantly over estimated if oxide variation is ignored.

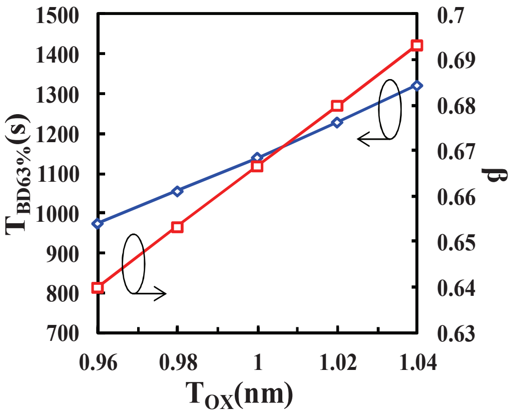

Fig. 5: Weibull slope (β) and the mean time to breakdown ($T_{BD63\%}$) as function of oxide thickness. V_{STRESS}=1V.

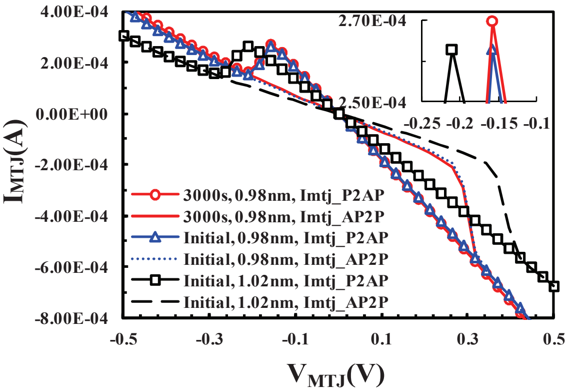

Fig. 6: I-V characteristics of MTJ with different oxide thicknesses (0.98nm and 1.02nm) and stress times (0s and 3000s). Inset figure shows the increase of I_C after stress.

Fig.6 shows that the slope of I-V curve of MTJ decreases with the increase of oxide thickness corresponding to the increased resistance. Furthermore, although the critical current does not change for different oxide thickness, it increases with stress time due to the impact of BDs, as shown in the inset of Fig. 6.

In Fig. 7, it is observed that anti-parallel resistance (R_{AP}) of MTJ decreases with stress time due to the increased number of BD paths. Though MTJ with thicker oxide are supposed to suffer less BD events, it shows slightly larger degradation. It can be attributed to the fact that the impact of BD path is larger in the MTJ with thicker oxide since it causes larger degradation when the resistance is larger. The Tunneling Magneto Resistance (TMR) decreases with stress time due to the larger degradation of anti-parallel resistance as compared to that of parallel resistance. The weak dependence of "initial" TMR on oxide thickness is randomized by the statistics of BD events.

Fig. 8a shows a significantly larger spread of R_{AP} as oxide thickness variation is considered. Interestingly, as shown in Fig. 8b, although the standard deviation (σ_{RAP}) increases with stress time in the beginning (no T_{OX} variation is considered), it gradually saturates. In fact, there are two factors which modulate σ_{RAP}; the first factor is the statistics of BD event which tends to increase σ_{RAP}. The second is the unequal impact

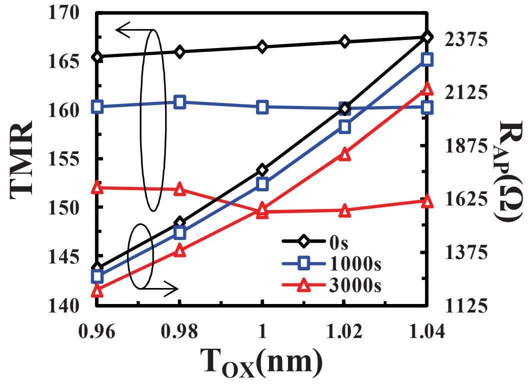

Fig. 7: TMR and R_{AP} as function of oxide thickness for different stress times: 0s, 1000s and 3000s. V_{STRESS}=1V. Both TMR and R_{AP} degrade with stress time.

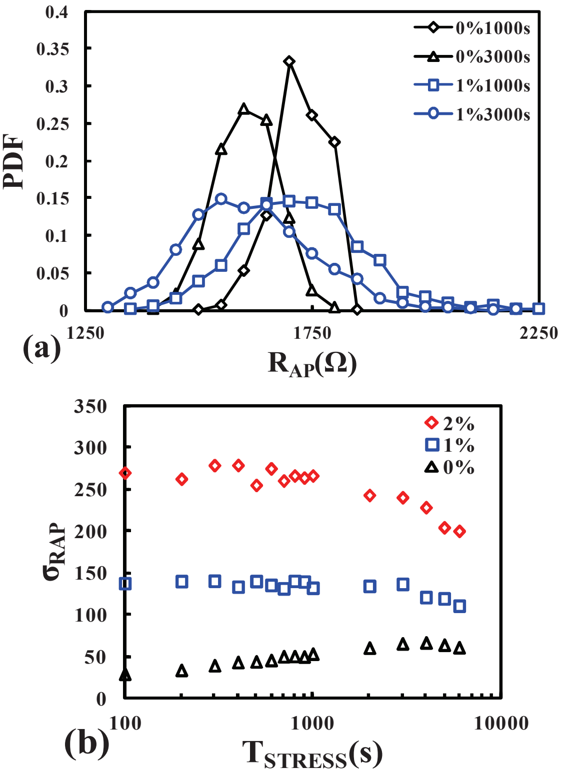

Fig. 8: (a) R_{AP} distribution with different stress time (1000s and 3000s) assuming constant oxide thickness and normal distribution of oxide thickness with standard deviation of 1%. (b) Standard deviation of R_{AP} as a function of time with different variations in oxide thickness (0%, 1% and 2%)

of BD path on large and small resistance which decreases the spread. In the beginning of stress, since there is no spread of resistance, the second factor has no effect. Hence, the first factor dominates, which leads to the increase of σ_{RAP}. As R_{AP} starts to spread, the impact of second factor starts to increase and is finally comparable to the first factor which results in saturation (Fig. 8b). On the other hand, when T_{OX} variation is considered, the initial variation for resistance is large leading to the domination of second factor and, hence, σ_{RAP} decreases with time, as shown in Fig. 8b.

Fig. 9a illustrates that the critical current (J_C) increases with stress time. However, it is observed that MTJs with thinner oxide, which are expected to have more BD events, have smaller degradation. It can be attributed to the fact that the state of the MTJ switches at a smaller voltage for smaller T_{OX} (Fig. 6). The smaller voltage causes decrease of post-BD current significantly, leading to smaller degradation, as illustrated in Fig. 2. Fig. 9b shows that, unlike σ_{RAP} in Fig. 8b, the standard deviation of J_C (σ_{JC}) increases with time and the increase in the oxide thickness variation.

IV. CONCLUSIONS

In this work, a physics-based statistical model is proposed for evaluation of the time-dependent STT-MRAM performance. The model considers process variations -- variations in the thickness of the tunneling oxide. Using this model, the impact of oxide thickness variation on the statistics of critical current and resistance of MTJ are rigorously examined. The proposed model can be used as a guide for evaluation of design margin for better life-time of STT-MRAM.

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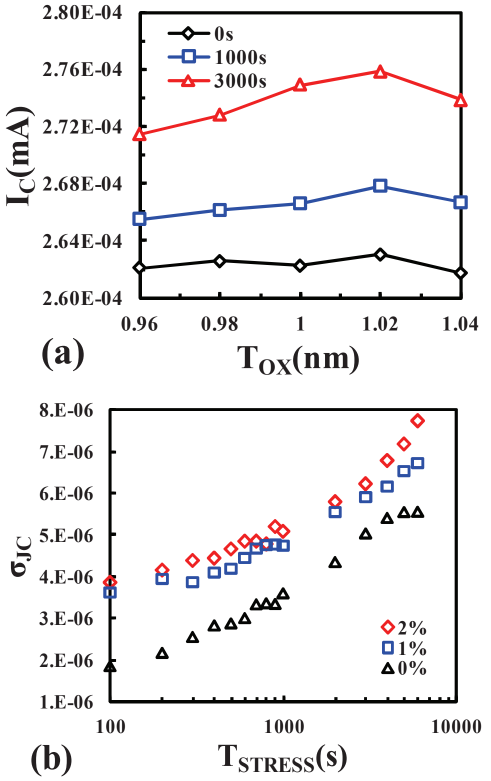

Fig. 9: (a) Critical current as a function of oxide thickness for different stress times: 0s, 1000s and 3000s. V_{STRESS}=1V. (b) Standard deviation of I_C as a function of time with different variations in oxide thickness (0%, 1% and 2%)

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