A Comprehensive Study on Interface Perpendicular MTJ Variability

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Spin transfer torque MRAM (STT-MRAM) is one of the promising candidates as a scalable nonvolatile memory with high density, and CMOS compatibility [1], [2]. Interface perpendicular magnetic tunnel junction (PMTJ) shown in Fig. 1 has been demonstrated with the goal of reducing the switching current while maintaining sufficient nonvolatility [3]. However, previous studies report that PMTJ suffers from process-dependent dimensional variations, thus it remains one of the major constrains in achieving high performance STT-MRAM [4, 5]. As shown in the equations of Fig. 1, the anisotropy field (H_K) and free layer volume (V) are functions of PMTJ dimensions, hence their variations result in variation of STT switching characteristics such as thermal stability factor (Δ) and switching current (I_C). The H_K of PMTJ has a strong dependency on relative ratio between the free layer thickness (t_F) and the critical thickness (t_C) [3]. The equations of Fig. 1 suggest that the t_F variation differently affects the PMTJ dimension-dependent parameters (gray circles), resulting in either increasing or decreasing Δ and/or I_C. This paper presents a comprehensive study on process-dependent dimensional variability of PMTJ, especially focusing on estimating the impact of t_F variation on Δ and I_C variability. For a practical analysis, our physics-based macrospin SPICE model [7] captures the key physics of STT switching in PMTJ by incorporating all of the above mentioned PMTJ dimension-dependent parameters into the Landau-Lifshitz-Gilbert (LLG) equation.

The variation factors and realistic PMTJ material parameters [3], [5], [6] used in this work are listed in Table 1. Our variability analysis is based on determining the degree of Δ for a target chip failure rate. Here, we assume a STT-MRAM L3 cache with 64MB density for server processor as a target memory system. The $7.95\text{x}10^{-7}$ chip failure rate is set by the repair capability and corresponding Δ of 70 for 10 years of retention is estimated [8]. A double MgO interface [5] is considered to scale the I_C down and increase the Δ for meeting the system specification. The t_F-dependent damping factor (α) in CoFeB is also considered for realistic analysis. To estimate the impact of process-dependent dimensional variations on PMTJ variability, appropriate values of the variation (3σ/μ) in the free layer width and length are set to 12% according to the ITRS roadmap. Moreover, the variation (3σ/μ) of t_F is varied from 4% to 9% with 1% step to evaluate its dependency on Δ and I_C variability. Each variation parameter is assumed to have a normal distribution with ±3 standard deviation (σ). The Monte Carlo simulator extracts the 1000 random variables with ±3σ for all the above mentioned dimension-dependent parameters, then, our simulation model estimates each I_C, Δ, and $t_{retention}$ variability for a given switching time (t_{sw}).

Fig. 2(a) shows the simulated I_C as a function of t_{sw} at 50% switching probability. Note that our model demonstrates realistic dynamic spin motions based on measured data [9]. A constant t_{sw} of 5ns was chosen for following variability simulations. As shown in Figs. 2(b) and 3, each I_C, Δ, and $t_{retention}$ variability has Gaussian distribution under free layer W, L variation of 12% and t_F variation of 4%. Fig. 4 shows the t_F variation dependency on Δ variability. Simulation result indicates that the Δ variability has a strong linear dependency on t_F variation. Variability trend of $t_{retention}$ is projected directly from the variability trend of Δ [5]. Fig. 5 shows correlation maps between $t_{retention}$ and I_C variability under different t_F variation conditions (4%, 9%). It offers a clear comparison of impact of t_F variation on $t_{retention}$ and I_C variability. The slope (ΔI_C / $\Delta t_{retention}$) difference suggests that the $t_{retention}$ variability has a stronger dependency on t_F variation compare to I_C variability counterpart. Moreover, over 40% Monte Carlo random samples do not meet a retention time of 10 years for both different t_F variation cases. Increasing Δ shown in Fig. 6 would be considered to make all of random samples meet a target of 10 years retention [10]. However, I_C increase is unavoidable for increasing Δ. After increasing Δ, the correlation maps are replotted in Fig. 7 compared to Fig. 5 (gray dots). Results shown in Table 2 indicate that the 2.3x steeper slope (ΔI_C / $\Delta t_{retention}$) under 4% t_F variation compare to 9% counterpart offers smaller Δ increase (82 rather than 87), requiring a 0.6x smaller I_C increase to make all of random samples have a longer retention time than 10 years.

In conclusion, we quantify the impact of t_F variation on Δ and I_C variability in PMTJ. The Δ variability shows considerable t_F variation dependency compared to I_C variability counterpart, offering smaller increase of Δ and I_C as t_F variation is improved to make all of random MTJ samples meet a retention time specification.

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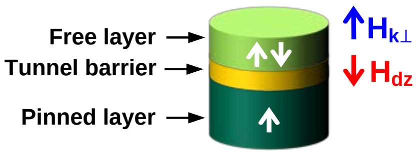
References: [1] S. Wolf, et al., *Proc. IEEE*, 2010, pp. 2155-2168. [2] K. Lee, et al., *Trans. Magn.*, 2011, pp. 131-136. [3] S. Ikeda, et al., *Nature Mater.*, 2011, pp. 721-724. [4] H. Sato, et al., *APL*, 2011, pp. 042501. [5] K. Tsunoda, et al., *IEDM*, 2014. [6] J. Hayakawa, et al., *Jpn. JAP*, 2005, pp. L587-L589. [7] J. Kim, et al., *DRC*, 2014. [8] K.C. Chun, et al., *JSSC*. 2013, pp. 2240-2243. [9] H. Zhao, et al., *JAP*, 2011, pp. 07C720. [10] K. Hofmann, et al., *VLSI Tech. Symp*. 2014.



$$\Delta = \frac{H_k \cdot M_s \cdot V}{2k_B T} \qquad H_{k\perp} = \frac{K_i}{t_F} - 4\pi \cdot N_{dz} \cdot M_s$$

$$I_C = \frac{2e \cdot \alpha \cdot M_S (H_{k\perp} - 4\pi \cdot N_{dZ} \cdot M_S) \cdot V}{\hbar \cdot \eta}$$

(grey circle) : a function of PMTJ dimensions

Fig. 1. The anisotropy field (H_k), thermal stability factor (Δ), and switching current (I_C) in interface perpendicular magnetic tunnel junction (PMTJ) show a strong dependency of process-dependent dimensional variations.

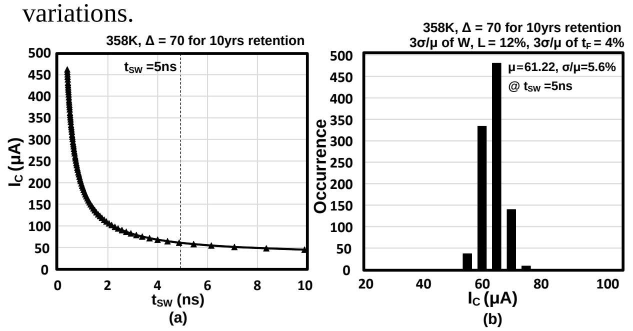


Fig. 2. (a) I_C as a function of t_{sw} and (b) I_C variation under free layer W, L variation of 12% and t_F variation of 4% (t_{sw}=5ns).

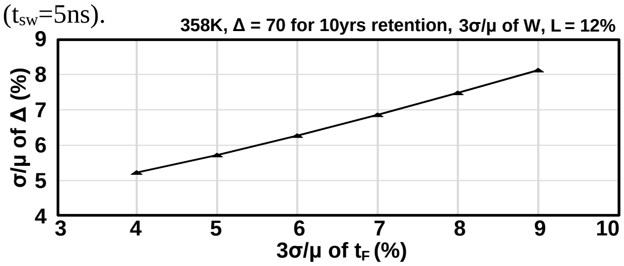


Fig. 4. The Δ variability has a strong dependency on t_F variation.

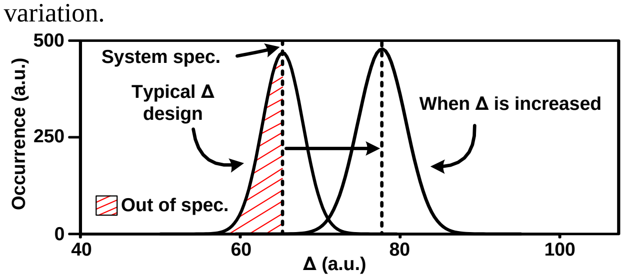


Fig. 6. Increasing Δ would be considered to make all of random samples meet a target of 10 years retention [10].

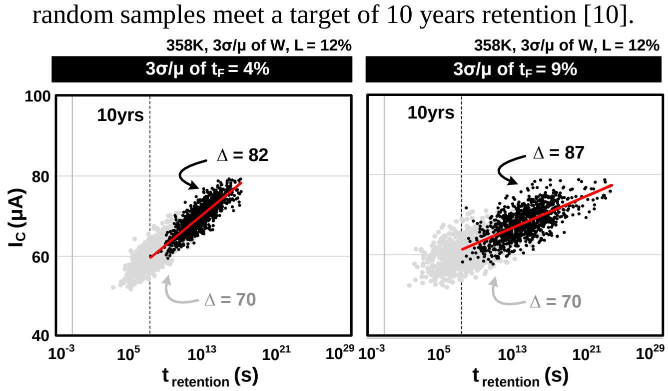


Fig. 7. Replotted correlation maps after increasing Δ.

64MB L3 cache memory, Δ = 70 for 10yrs retention

Quantity	PMTJ [3], [5], [6]
Anisotropy source	Interface
Sat. Magnetization, M_S (10^3A/m)	1077
Polarization factor, P	0.6
Effective critical thickness, t_C (nm)	3 (1.5 x 2, double MgO interface*)
Gilbert Damping, α	t_F dependent**
Length, width of free layer, L, W (nm)	μ=22, μ=22 (3σ/μ=12%***)
Thickness of free layer, t_F (nm)	μ=2.78 (3σ/μ=4***~9%)

* To increase the Δ for 10yrs retention, double MgO interface is used [5]
** t_F dependent α is used [3], *** ITRS roadmap

Table 1. Variation factors and realistic PMTJ material parameters used in the variability analysis.

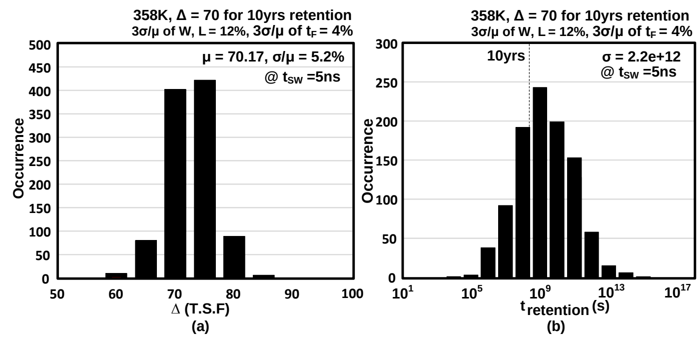


Fig. 3. Variation of (a) Δ and (b) $t_{retention}$ under free layer W, L variation of 12% and t_F variation of 4%.

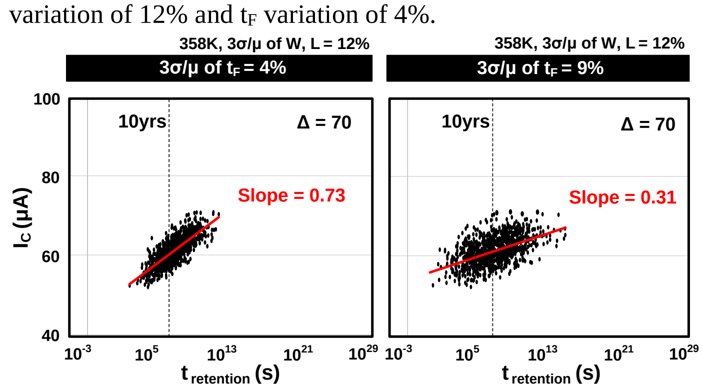


Fig. 5. Correlation maps between $t_{retention}$ and I_C variability under different t_F variation conditions (4%, 9%). A slope (ΔI_C / $\Delta t_{retention}$) difference suggests that the $t_{retention}$ variability has a stronger dependency on t_F variation compare to I_C variability counterpart.

358K, 3σ/μ of W, L = 12%

Quantity		3σ/μ of t_F = 4%		3σ/μ of t_F = 9%	
Typical Δ design	Δ for 10yrs $t_{retention}$	70		70	
		Avg.	σ/μ	Avg.	σ/μ
	I_C (μA)	61.22	5.6%	61.31	5.7%
	Δ	70.17	5.2%	70.27	8.1%
	ΔI_C / $\Delta t_{retention}$ (μA/s)	0.73 (2.3x)		0.31 (1x)	
When Δ is increased	Δ for $t_{retention,Min}$ > 10yrs	82		87	
		Avg.	σ/μ	Avg.	σ/μ
	I_C (μA)	68.11	5.7%	72.03	5.7%
Remark (required I_C for increasing Δ)		6.89μA (0.6x)		10.72μA (1x)	

Table 2. The 2.3x steeper slope (ΔI_C / $\Delta t_{retention}$) under 4% t_F variation compare to 9% counterpart offers smaller Δ increase (82 rather than 87), requiring a 0.6x smaller I_C increase to make all of random samples have a longer retention time than 10 years.