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Size Dependence of Thermal Stability Factor in Perpendicular CoFeB/MgO MTJ Studied by Micromagnetic Simulations

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Abstract

Size dependence of the thermal stability factor (Δ) for the perpendicular CoFeB/MgO based magnetic tunnel junction (p-MTJ) was investigated using the string method in the framework of finite element micromagnetics. The simulation revealed that Δ shows significant size dependence on MTJ size and the reversal mode change from coherent rotation to domain wall motion as MTJ size increases. This Δ simulation can reproduce the experimental data consistently and might be helpful for MTJ devise design.

1. Introduction

Spin transfer torque (STT) MRAM is a promising candidate for next-generation high-density non-volatile memory due to its good scalability, high-speed operations, and high endurance. As technology scales down, MTJ size of less than 30 nm will be required [1], which accompanies the reduction of Δ. The Δ is a key parameter to use for the device design and reliability prediction.

As for the determination of Δ, the method of pulse magnetic field application to measure a switching probability has been widely used. However, it was reported that the measured Δ is almost independent of device size above ~30 nm [2]. By contrast, the Δ obtained from the data retention measurement of MTJ array at higher temperature exhibits substantial size dependence [3, 4]. The evaluated Δ was inferred to be more accurate and explained by an analytical model based on domain-wall (DW) propagation [4]. Note that this Δ is a median value which includes variations due to the process variations. Recently, it was proposed a thermal disturbance method that the accurate Δ value of single MTJ can be obtained [5, 6].

In this study, we performed the Δ calculations using micromagnetic simulation with the string method [7] to study the size dependence of the Δ for a perpendicular CoFeB/MgO–MTJ and understand their magnetization reversal behavior.

2. Simulation method and device structure

We have developed to finite element method (FEM) based full micromagnetic simulator EXAMAG [8] incorporating the string method for finding a minimum energy path (Fig. 1). A thermal stability factor of P-state, Δ_P (AP-state, Δ_{AP}) can be defined as the difference between the P-state (AP-state) and highest energy point (the saddle point) on the path.

Figure 2(a) shows stack structures of a CoFeB/MgO MTJ (similar MTJ structure described in [6]) employed in this study. Sidewall angle of MTJs were set to 75°. The stray field from the reference layer and interlayer exchange coupling between ferromagnetic layers were taken into account exactly in the simulation. The material parameters used for the Δ calculations are summarized in Fig. 2(b).

3. Results and discussion

Figure 3 shows the size dependence of calculated Δ at 300 K for the CoFeB/MgO-MTJ. The exchange stiffness constant (A_{ex}) was set to 10 pJ/m. The Δ shows significant size dependence even at MTJ size above ~40 nm and good agreement with the experimental data. Note that the Δ_{PtoAP} is larger than Δ_{APtoP} for all MTJ sizes. This is due to the stray field from the pinned layer. Figure 4 shows the minimum energy paths for the MTJ at the size of (a) 20 nm and (b) 60 nm. Corresponding domain images are shown along the path. The switching is occurred nearly coherently for 20 nm-MTJ, while it mediated by DW for 60 nm-MTJ. By examine the domain image of all size, it is found that the reversal mode changes from coherent rotation to DW motion at the MTJ size of 30 nm.

In addition, switching mode can be changed from DW motion to coherent rotation by changing A_{ex} even for the MTJ with same size. Figure 5(a) shows the calculated Δ and minimum energy paths for the 30 nm-MTJ at A_{ex} = 5, 10, and 15 pJ/m. Note that reversal by DW motion results in a lower Δ than coherent rotation and crossover of both mode was observed at A_{ex} = 10 pJ/m. Phase diagram of reversal mode for the CoFeB/MgO-MTJ is shown in Fig.6. Crossover between coherent rotation and DW motion moves to larger size at larger A_{ex}.

We found that the size dependence of Δ and the switching mode can be reproduced simply by changing the MTJ size using the same physical parameters.

4. Conclusion

We investigated the size dependence of Δ for perpendicular CoFeB/MgO-MTJ using micromagnetic simulation adopted string method. We showed that Δ exhibits significant size dependence and the reversal mode changes from coherent rotation to domain wall motion as the MTJ size increases. Furthermore we found that the Δ simulation can reproduce the experimental data consistently and might be helpful for MTJ devise design.

References

[1] J. J. Kan et al., IEDM p 671, 2016.
[2] H. Sato et al., Appl. Phys. Lett., 105, 062403.
[3] K. Tsunoda et al., IEDM p 486, 2014.
[4] L. Thomas et al., IEDM, p 672, 2015.
[5] S. Saito et al., IEEE Tran. Magn. 54, 3400505(2018).
[6] E. C. I. Enobio et al., Jpn. J. Appl. Phys 57, 04FN08 (2018).
[7] W. E. et al., Phys. Rev. B66, 052301 (2002).
[8] Fujitsu Ltd. [Online]. Available: http://www.fujitsu.com/global/about/resources/news/press-releases/2013/1210-01.html

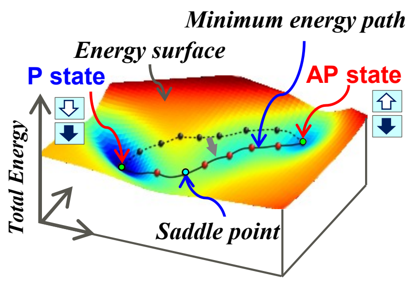
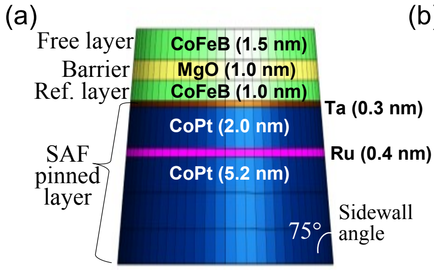


Fig .1 Schematic of minimum energy path. The thermal stability of P-state Δ_P (Δ_{AP}) is defined as the difference between a stable P- (AP-) and highest energy point (the saddle point) on the path.



(b)

Material	M_s (T)	H_k (T)	J (erg/cm^2)
CoFeB-free	1.1	1.2	
MgO			0.01
CoFeB-ref.	1.1	2.2	
Ta			0.1
CoPt	0.9	2.5	
Ru			-0.69
CoPt	0.9	2.5	

Fig .2 (a) Schematic structure of p-MgO MTJ and (b) summary of material parameters used for the simulation. M_s is saturation magnetization which include the effect of dead layer, H_k is anisotropy field which does not include the demagnetization field, and J is exchange coupling strength.

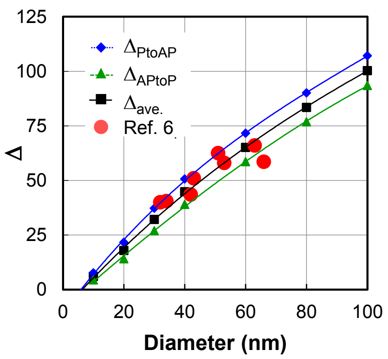


Fig .3 Δ for the CoFeB/MgO MTJs calculated by changing MTJ diameter. Red circle shows the experimental data from ref. 6.

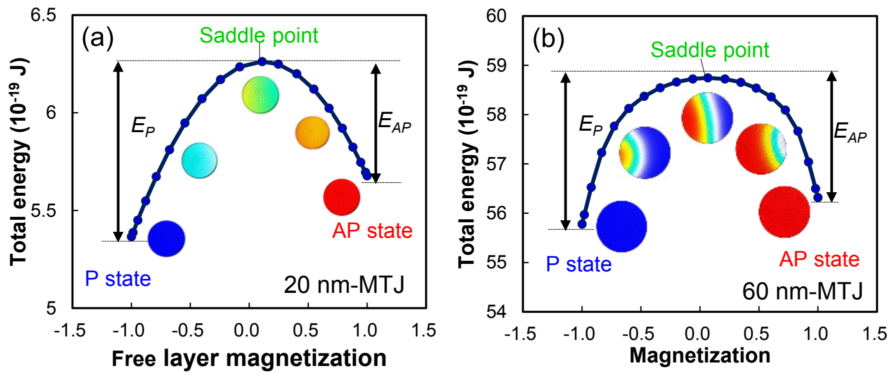


Fig .4 Minimum energy paths for the CoFeB/MgO-MTJs at the size of (a) 20 nm and (b) 60 nm. Corresponding domain images of free layer are shown along the path. The colors refer to the z-component of magnetization (red positive, blue negative direction). Switching is occurred nearly coherently for 20 nm-MTJ, while it mediated by domain-wall for 60 nm-MTJ.

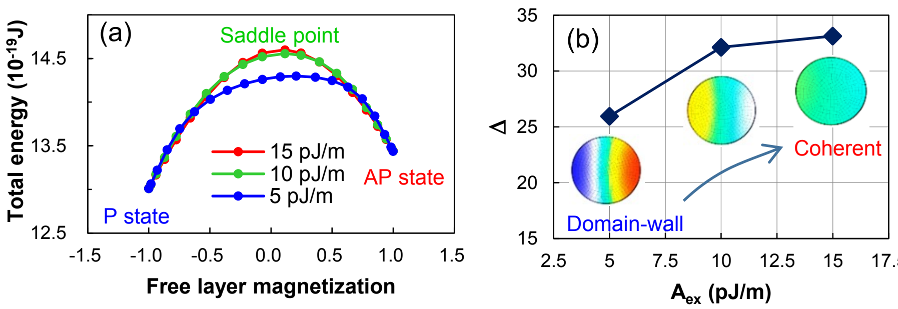


Fig .5 (a) Minimum energy path and (b) Δ for 30 nm-MTJ at A_{ex} = 5, 10, and 15 pJ/m. Inset shows the domain images of the free layer at saddle points. The reversal mode changes from coherent to domain wall motion at A_{ex} = 10 pJ/m.

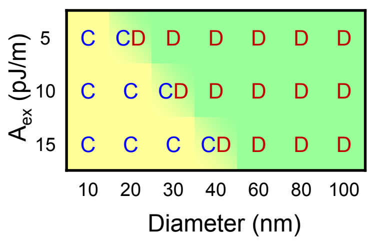


Fig. 6 Phase diagram of reversal mode as a function of A_{ex}. “C”, “D”, and “CD” indicate coherent rotation, DW motion, and crossover of both mode, respectively.