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LLG Micromagnetic Simulation on STT Efficiency of sub 30nm Perpendicular MTJs with etching damage

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Abstract

STT efficiency of p-MTJs with the free layer diameter *d* from 10 to 30 nm was evaluated using LLG micro-magnetic simulation. The STT efficiency for MTJs with the etch-damaged sidewall increases with a decrease in *d*, which is different from that without the damage. The STT efficiency for MTJs with the conical shape slightly decreases with a decrease in *d*.

1. Introduction

Spin Transfer Torque (STT) MRAM is one of the promising candidates for a new class of non-volatile memory[1-4]. To scale STT-MRAM, it is essential to realize the high STT efficiency Δ/I_{c0} for MTJs with the diameter of the free layer d below 30 nm, where Δ is the thermal stability factor and I_{c0} is the threshold current. CoFeB/MgO based MTJs with perpendicular anisotropy (p-MTJs) [5] is expected to realize high STT efficiency in the region of the MTJ diameter below 30nm[6,7]. Recently, for CoFeB/MgO based p-MTJs with d of less than 40 nm, Sun *et al*. reported that STT efficiency increases with a decrease in d[8]. This article suggested that this is attributed to an edge-fringe-field related reduction in demagnetization energy. On the other hand, several reports suggested that etching damage has an effect on the properties of MTJs, such as coercive force or MR ratio[9, 10]. In addition, the real shape of a MTJ is not completely cylindrical. Therefore, it is possible that these factors can affect the STT efficiency. In this article, we investigate the effect of etching damage and the shape on STT efficiency using LLG micromagnetic simulation.

2. Method

The film stack of p-MTJs was CoFeB(1.3 nm)/MgO(1 nm)/antiferromagnetic-coupled reference layer. The saturation magnetization M_s, perpendicular anisotropy constant K_u, and the damping constant α of the CoFeB free layer were 1257 emu/cm^3, 1.0x10^7 erg/cm^3 and 0.005, respectively. Although the real antiferromagnetic-coupled reference layer consists of lots of magnetic/nonmagnetic films[11], we approximated it by a simple ferromagnetic (FM1)/Ru(0.8 nm)/ferromagnetic (FM2) tri-layer for calculations. The thickness, M_s, K_u and α of the FM1 layer were 2.2 nm, 1.05 emu/cm^3, 1.3x10^7 erg/cm^3 and 0.1, respectively. The thickness, M_s, K_u, and α of the FM2 layer were 3.3 nm, 0.8 emu/cm^3, 1.3x10^7 erg/cm^3 and 0.1, respectively. The spin polarization of three ferromagnetic layers was 0.6.

In case of studying the effect of etching damage, we reduced M_s of three ferromagnetic layers with the width of 2 nm near the pillar sidewall as shown in Fig.1 (b). In case of evaluating the STT efficiency of the MTJ whose shape is conical, we used the model structure that the diameter of the free layer was 1 nm smaller than that of the reference layer as shown in Fig.1 (c).

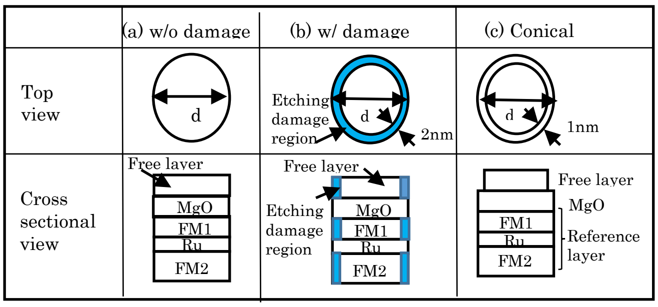

Figure 1 MTJ pillar structure used in simulation

We used the commercially available LLG codes for our simulation[12]. The spin torque coefficient for MTJs given by Slonczewski[13] is used in this simulator. The lateral cell size was fixed to 2 x 2 nm for the cylindrical shaped MTJs and 1 x 1 nm for the conical shaped MTJs. The time step for numerical time integration was 0.025 ps. All calculations were executed at T = 0 K.

When the diameter of a MTJ is enough small, the relationship between the switching time t_{SW}, and switching current density J is expressed by the well-known macro-spin theory[14],

$$(J/J_{c0} - 1)\, t_{SW} = \ln(\pi/2\theta_0)/\alpha\gamma H_{eff}, \qquad (1)$$

where J_{c0} is the threshold current density, γ is the gyromagnetic constant, H_{eff}, is the effective anisotropy magnetic field, and θ_0 is the initial misalignment angle of magnetization of the free layer to the easy axis. We calculated t_{SW} changing J, and evaluated J_{c0} and H_{eff} by fitting the calculated data. Then, using the equation $\Delta/I_{c0} = (M_s H_{eff} t_f)/(2k_B T J_{c0})$, we evaluated the STT efficiency, where k_B is the Boltzmann constant and t_f is the thickness of the free layer.

3. Results and Discussion

Figure 2 compares J_{c0} H_{eff}, and Δ/I_{c0} of MTJs between with etching damage and without etching damage. In all cases, J_{c0} and H_{eff} increased with a decrease in *d* as shown in Fig. 2 (a)-(b). These are attributed to a decrease in the net demagnetization field perpendicular to the film plane when the pillar diameter decreases[15]. Δ/I_{c0} for MTJs without etching damage was nearly constant as a function of *d* as shown in Fig.2 (c), which indicates that a decrease in the net demagnetization has the effect on both J_{c0} and H_{eff} at the same level. On the other hand, Δ/I_{c0} for MTJs with M_s reduction near the pillar sidewall increased with a decrease in *d* as shown in Fig. 3 (c). While M_s reduction decreases the demagnetization field near the pillar sidewall and locally increases the perpendicular anisotropy constant, it reduces the net magnetization of a free layer. Therefore, an increase in J_{c0} is smaller than that in Δ, resulting in an increase in STT efficiency with a decrease in *d*. Comparing our results with the previous experiments[8], the dependence of STT efficiency on *d* was reproduced. However, J_{c0} in the previous experiments[8] is not strongly dependent on *d*. According to the suggestion in the previous article, we calculated J_{c0} as a function of *d* when the exchange stiffness constant of the bottom interface layer in the free layer was reduced. As a result, an increase in J_{c0} with a decrease in *d* was smaller, but an increase in STT efficiency was also smaller. This results indicate that there may be other mechanism beyond the previous model[8].

Figure 3 shows J_{c0} H_{eff}, and Δ/I_{c0} of MTJs when the pillar shape was modeled to be conical. J_{c0} and H_{eff} was not strongly depend on *d*, which was different trend from those in Fig.2. STT efficiency slightly decreased at *d* = 10 nm. This may be due to the reduction in the stray field from the reference layer which is strong at the edge of the pillar.

4. Conclusion

We evaluated the STT efficiency as a function of *d* (from 30nm to 10nm) when M_s near the MTJ pillar sidewall decreased or the shape of the MTJ was conical, using LLG micromagnetic simulation. The STT efficiency of MTJs with the small M_s region increased with a decrease in d. On the other hand, the STT efficiency of MTJs with the conical pillar shape slightly decreased when *d* was very small. Although the former results reproduced the trend in the previous experiments, the trend of J_{c0} was not reproduced, indicating that there may be other mechanism beyond the previous model.

Acknowledgements

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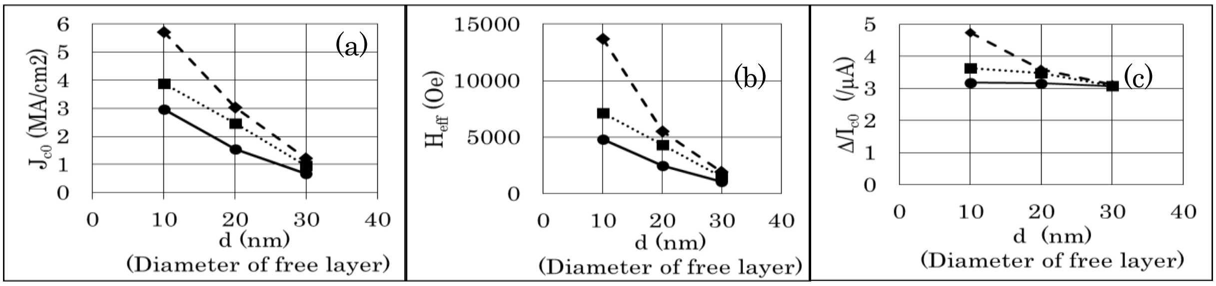

Figure 2 Dependence of J_{c0}, H_{eff}, and STT efficiency on diameter *d* of the free layer in p-MTJs for parallel to anti-parallel magnetization reversal when Ms near the pillar wall decreses. The pillar shape is cylindrical. (a) J_{c0}, (b) H_{eff}, (c) STT efficiency. (● No damage, ■ 0.8Ms near the pillar wall, ◆ 0.5Ms near the pillar wall)

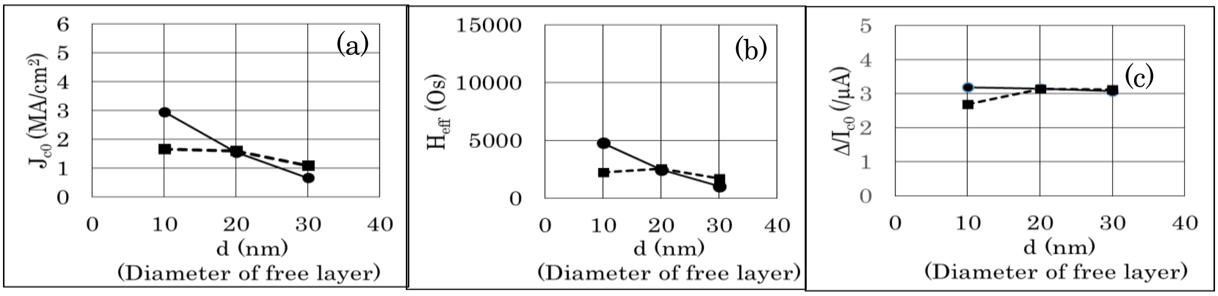

Figure 3 Dependence of J_{c0}, H_{eff}, and STT efficiency on *d* of the free layer in p-MTJs for parallel to anti-parallel magnetization reversal when the pillar shape is conical. . (a) J_{c0}, (b) H_{eff}, (c) STT efficiency (● MTJ shape is cylindrical. ■ MTJ shape is conical.)