G-6-3(Invited)

Extended Abstracts of the 2009 International Conference on Solid State Devices and Materials, Sendai, 2009, pp1198-1199

Advancements and Future Challenges of Spin Torque Transfer MRAM

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1. Introduction

MRAMs (Magnetoresistive Random Access Memory) have been actively developed as non-volatile work memories because MRAMs have attributes of unlimited endurance and fast read/write speed which none of other non-volatile memories have.

An early work on field switching MRAMs proved the attributes [1]. However the MRAMs seem to lack in scalability beyond 256Mbit. Recent works have been done on spin torque transfer MRAMs [2], [3]. Most of the MTJs (Magnetic Tunnel Junctions) were made of elements with longitudinal shape anisotropy, i.e. in-plane MTJs. The critical switching currents, Ic, were hundreds microamperes and exceeded conventional CMOS drivability of write current at Gbits density. Perpendicular MTJs were proposed to solve this problem [4], [5], [6], [7], [8], [9], [10].

In this paper, a very small Ic of 9 microamperes is achieved with a newly developed perpendicular storage material, an Fe alloy, and the superiority of perpendicular MTJs over in-plane MTJs on Ic is clarified. Moreover, future challenges of the perpendicular MTJs are discussed.

2. Reducing critical switching currents, Ic, by perpendicular MTJs

A main issue for spin torque transfer MRAMs is the large Ic. The typical drivability is about 1 milliampere per 1 micrometer gate width, i.e. about 65 microamperes for Gbits density.

Analytic expressions of Ics are given by below [4].

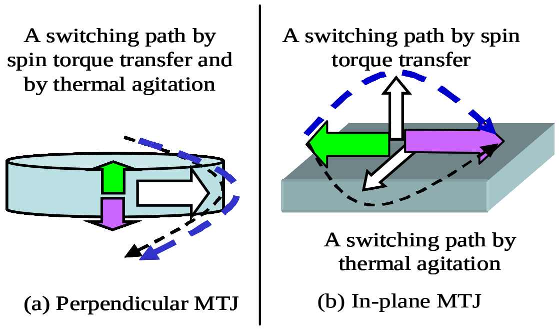
$$I_{c0}(\textit{in-plane}) = \frac{2\,e\,\alpha}{\hbar\,g(\theta)}\left(2\,\Delta E + 2\,\pi\,Ms^{2}\,t\,F^{2}\right) \quad (1)$$

for in-plane MTJs.

$$I_{c0}(\textit{perp.}) = \frac{2\,e\,\alpha}{\hbar\,g(\theta)}\left(2\,\Delta E\right) \quad (2)$$

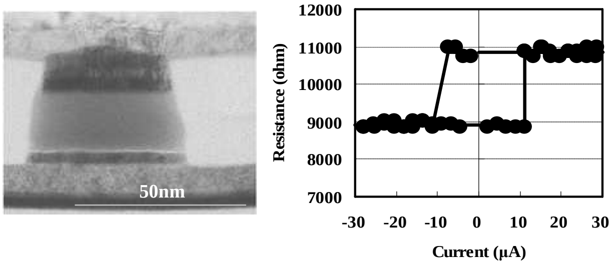
for perpendicular MTJs.

Here I_{c0} is defined as a critical switching current with 1nsec. pulse. The e, α, hbar, g(θ), ⊿E, Ms, t, and F are electronic charge, damping constant, reduced Planck's constant, spin transfer efficiency, the storage energy, saturation magnetization, thickness of a storage layer, and a feature size of MTJs. The Ic for perpendicular MTJs gets smaller by the second term in (1), demagnetization term, than that for in-plane MTJs. Figure 1 illustrates the reason. In perpendicular MTJs, both spin torque transfer and thermal agitation make the magnetization take a path of lying in-plane in switching where the systems take maximum energy. While, in in-plane MTJs, only spin torque transfer makes the magnetization take a path of standing perpendicular to the plane where the system takes maximum energy. Thermal agitation makes the magnetization take a path of lying in-plane throughout switching. Thus, perpendicular MTJs have the potential to have large ⊿E/Ic. The ⊿E/Ic is a figure of merit, i.e. an efficiency of spin transfer torque writing. In this study, an Fe alloy is selected as the storage layer because it has a small intrinsic damping constant of about 0.01. The film thickness was set between 1.5nm and 2.0nm to have the reasonable ⊿E for the experiments. MTJs were patterned into cylinders with about 50-55nm diameter. The TEM image and the hysteresis curve are shown in Figure 2. The Ic for anti-parallel to parallel switching is 9 microamperes and that for parallel to anti-parallel switching is 11 microamperes. Those are far smaller than those ever reported. The storage energy is estimated $32k_BT$ by its coercivity dependence on sweep rate of applied magnetic field.



(a) Perpendicular MTJ (b) In-plane MTJ

Fig.1 Comparison on switching paths between perpendicular MTJ and In-plane MTJ



(a) A TEM image (b) A hysterics curve

Fig.2 A TEM image and small critical switching currents of an MTJ with an Fe alloy storage layer

Table 1 A list of spin torque transfer data for perpendicular MTJs and an in-plane MTJ

Materials of a storage layer		Perpendicular				In-plane	
		TeFeCo	CoFe super lattice	Fe Alloy		CoFeB	
Coercive field(Oe)		1200	1560	852	207	-	-
Volumes of the storage layer(nm^3)		dia.130x4t	dia.100x2.5t	dia.50x1.5t	dia.50x1.5t	120x240x**t	100x170x**t
⊿E (kBT)		107	114	45	32	43	34
MR(%)		10	60	22	23	>100	>160
Experimental data	Ic(microampere)	398	212	46	9	130	330
	Current pulse width(nsec.)	100	100	30	5000	30000	10
Estimated Ic with pulse width of 50nsec.(microampere)		401	213	45	11	155	314
(⊿E/kBT) /(The estimated Ic)		0.27	0.53	1	2.9	0.27	0.11

3. Comparison between perpendicular MTJs and in-plane MTJs on critical switching currents.

Table 1 summarizes the demonstration data done so far [2], [5], [6], [7], [11]. For the purpose of comparison, only Ics for anti-parallel to parallel switching are listed.⊿Es are estimated by either the same experiments as in case of the above Fe alloy experiment or their Ic dependence on current pulse width.

The ($\varDelta E/k_BT$)/Ic for an in-plane MTJ is small even with the small damping constant of CoFeB and the large MR of 100-150%. While, the ($\varDelta E/k_BT$)/Ic for perpendicular MTJs are larger than that of the in-plane MTJ. Especially, that for Fe alloy is as large as 1-2.9 even with small MR of 22-23%. Thus, it is concluded that the efficiency of spin transfer torque writing for perpendicular MTJs is much higher than that for in-plane MTJs.

4. Possibility for Gbits density

The estimated Ic for the MTJ with 50nsec. pulse width is 11-45 microamperes which is smaller than the drivability of CMOS transistor at Gbits density. If the distribution of Is is controlled reasonably small, Gbit MRAMs can be realized. The analytic expression (2) says that an increase in MR leads to further reduction in Ic by making g(θ) larger. MR over 100-200% were reported for perpendicular MTJs [12],[13]. If MR over 100% is achieved, g(θ) almost doubles to reduce Ics from 11-45 microamperes to about 5-22 microamperes. Reducing the size also contributes to reduction in Ic [14]. MRAM over Gbits density is plausible.

4. Remaining issues of perpendicular MTJs for dense MRAMs

As far as the best data are concerned, most issues have been solved. Remaining issue is the control of the distributions. Especially, tightening the Ic distribution is the main issue. The distribution of MTJ size must be tightened.

4. Conclusions

The very small Ic of 9 microamperes is achieved with a newly developed perpendicular MTJ with Fe alloy storage layers. The efficiency of spin transfer torque writing for perpendicular MTJs is proved to be much higher than that for in-plane MTJs. The Ic for the MTJ with Fe alloy storage layer is within the drivability of CMOS transistors at Gbits density. Further reduction in Ic can be possible by an increase in MR and reduction in MTJ size. If a distribution of Ic can be controlled, over Gbits will be probable.

Acknowledgements

This work is supported by New Energy and Industrial Technology Development Organization (NEDO).

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