Current-induced instability of geometrically confined magnetic wall

Katsuyoshi Matsushita¹, Jun Sato¹, Hiroshi Imamura¹ and Munetaka Sasaki²
¹ Nanotechnology Research Institute (NRI), Advanced Industrial Science and Technology (AIST), AIST Tsukuba Central 2, Tsukuba 305-8568, Japan.
² Department of Applied Physics, Tohoku University, Sendai 980-8579, Japan.
E-mail: k-matsushita@aist.go.jp

Abstract. We investigated dynamics of the geometrically confined magnetic wall under huge current by using micromagnetic simulation in order to clarify the current-induced instability of the geometrically confined magnetic wall. We showed that the domain nucleation-annihilation oscillation appears above a threshold current and induces a voltage oscillation signal.

Geometrically confined magnetic walls in nano-scale contacts[1] have attracted enormous attention of researchers because of its potential applications to magnetoresistance (MR) devices [2, 3, 4, 5, 6, 7, 8]. The geometrically confined magnetic wall in a CoFe nano-contact generates a voltage oscillation signal under dc current density of the order of $10^9 \text{A/cm}^2$ in an experiment by Suzuki et al. [9]. The voltage oscillation signal implies that spin-wave instability of the geometrically confined domain wall is induced by spin-transfer torque[10, 11, 12, 13].

Spin-wave instability of magnetic structures induced by the spin-transfer torque under current have been investigated in magnetic bulk system, wires and films[14, 15, 16, 17, 18]. The threshold current density[18] where the spin-wave instability occurs depends on strength of the stray field and magnetic anisotropy. The feature of the current-induced instability of the geometrically confined magnetic wall has never been clarified. For the magnetic wall geometrically confined in the nano-contact, the threshold current density is almost zero because the stray field and magnetic anisotropy are negligible due to their characteristic lengths of the order of several or several ten nanometers, which are larger than the size of the nano-contact. However the zero threshold current density does not indicate that the geometrically confined magnetic wall is unstable under any current because a finite size effect due to the nano-contact inhibits the spin-wave excitation. In the present paper, to clarify the current-induced instability of the geometrically confined magnetic wall, we investigated its dynamics under huge current density by using a micromagnetic simulation and discussed the voltage oscillation signal due to the current-induced instability.

The spin-transfer torque is induced by spin accumulation[19]. We employed a finite element model of a nano-contact shown in Fig. 1 to evaluate the spin accumulation. Because the mean free path which is assumed to be that of CoFe of 3nm[20] is lesser than the system size, the spin accumulation, $\delta \vec{m}$ obeys the Zhang-Levy-Fert diffusion equation[21],

$$\frac{\partial}{\partial t} \delta \vec{m}(\vec{r}) = \nabla \left[ \beta \vec{S}(\vec{r}) \vec{J}_e(\vec{r}) + \hat{A}(\vec{S}(\vec{r})) \delta \vec{m}(\vec{r}) \right] + \frac{J_{sd}}{4 \pi} \delta \vec{m}(\vec{r}) \times \vec{S}(\vec{r}) + \frac{\delta \vec{m}(\vec{r})}{\tau}, \quad (1)$$
where $\vec{S}(\vec{r})$ denotes local magnetization; $\vec{j}_e(\vec{r})$, electronic current; $\beta$, polarization of resistivity; $D_0$, diffusion constant and $\tau$, a spin relaxation time. Equations (1) and (2) are solved numerically with combining the continuity equation for the electronic current, $\nabla \vec{j}_e(\vec{r}) = 0$. $\beta$ is taken to be that for conventional ferromagnets as $\beta = 0.65$. $D_0$ and $\tau$ are obtained, respectively, by the Einstein relation, $D_0 = C_0 / 2 e^2 N_F$ and $\tau = \lambda^2 / 2 D_0 (1 - \beta^2)$ for conventional values of conductivity, $C_0 = 700 \Omega^{-1} \text{nm}^{-1}$, spin diffusion length, $\lambda = 12 \text{nm}$, density of states at the Fermi level, $N_F = 7.5 \text{nm}^{-3} \text{eV}^{-1}$ and elementary charge $e$. On the top and bottom surfaces, we artificially adopted the boundary conditions that $\delta \vec{m} = 0$ and the current density of $\vec{j}_\text{in}$ is aligned in the z-direction. On the other surfaces, the natural boundary condition is employed. The simulated spin accumulation is nonuniform and concentrates on the contact region.

We adopted the classical spins on the simple cubic lattice with the lattice constant of $a = 0.4 \text{nm}$ to simulate dynamics of local magnetizations. We neglected the stray field and magnetic anisotropy because they are negligible in the experimental situation[9] as mentioned before. The Hamiltonian $\mathcal{H}$ is given by

$$\mathcal{H} = -J_{\text{dd}} \sum_{(i,j)} \vec{S}_i \cdot \vec{S}_j + J_{\text{sd}} \sum_i \vec{S}_i \cdot \delta \vec{m}_i$$

(3)

where the classical Heisenberg spin with its absolute value of unity, $\vec{S}_i$, expresses the direction of the local magnetization at the $i$-th site. $\delta \vec{m}_i$ denotes spin accumulation at the $i$-th site. The first and second terms in the right hand side of Eq. (3) express the exchange interaction between local magnetizations at nearest neighbor sites, and that between a local magnetization and spin accumulation at each site, respectively. The exchange coupling constant between local magnetizations, $J_{\text{dd}}$, is fixed at 0.04 eV which is of the order of the transition temperature of the order of $10^3 \text{ K}$ for CoFe. The exchange coupling constant $J_{\text{sd}}$ is set at 0.1 eV in accordance with Ref.[21]. Substituting the solution of Eqs. (1) and (2) for $\delta \vec{m}_i$ in Eq. (3), we evaluated the Hamiltonian of Eq. (3).
The dynamics of $\vec{S}_i$ is determined by the Landau-Lifshitz-Gilbert equation,

$$\frac{d}{dt} \vec{S}_i = \frac{\gamma}{1 + \alpha^2} \frac{\vec{S}_i}{\vec{S}_i^2} \times \left( \frac{\partial \mathcal{H}}{\partial \vec{S}_i} + \alpha \vec{S}_i \times \frac{\partial \mathcal{H}}{\partial \vec{S}_i} \right),$$

where $\gamma$ and $\alpha$ denote the gyromagnetic ratio scaled by saturation magnetization and Gilbert damping constant, respectively. The equation is numerically solved by a quaternion method[22]. The time step $\Delta t$ and $\alpha$ are set at $3.4 \times 10^{-2}$ fs and 0.02, respectively. The number of sites, $N_s$ is about $10^4$. For simplicity, we used the antiparallel boundary condition of the spins in order to simulate the experimental situation with a 180$^\circ$ wall. In the boundary condition, $\vec{S}$’s are fixed at (-1,0,0) on the surface of the top electrode and (+1,0,0) on that of the bottom electrode except for the lower surface of the top electrode and the upper surface of the bottom electrode. The directions of spins, $x$, $y$ and $z$ are defined as shown in Fig. 1. On the other surfaces the spins are free.

In order to investigate the collective dynamics of the geometrically confined magnetic wall, we calculated the magnetization, $\vec{M} = \sum_i \vec{S}_i/N_s$. The typical time evolutions of the magnetization are shown in Figs. 2 (a) and (b). For low $|\vec{j}_{in}|$ below the threshold current density $j_c \sim 10^{10}$ A/cm$^2$, an periodic oscillation of $M_x$ and $M_y$ is observed as shown in Fig. 2(a). The periodic oscillation is due to a magnetization rotation in the $M_x$-$M_y$ plane, which corresponds to a collective oscillation mode between the Bloch and Néel walls[23]. The other spin-wave excitation is very small because of the finite size effect due to the nano-contact.

Above $j_c$, the magnetization takes irregular oscillation[16, 17, 18] as shown in Fig. 2(b). In order to clarify the irregular oscillation in detail, we show a typical trajectory of $M_x$ in a short time interval in Fig. 3(a). The configurations of $S_x$ at a maximum and minimum of $M_x$ in the irregular oscillation are shown in Figs. 3(b) and (c), respectively. Each dashed line between black and white regions indicates a magnetic wall. We observe three magnetic walls in Fig. 3(b), and also observe single magnetic wall in Fig. 3(c). That is to say the irregular oscillation of $M_x$ shown in Fig. 3(c) (and that in Fig. 2(b)) corresponds to an oscillation between single- and triple-magnetic-wall structures due to current-induced domain nucleation-annihilation.

The irregular oscillation of $M_y$ and $M_z$ shown in Fig. 2(b) reflects the collective rotation of the local magnetization in the $S_y$-$S_z$ plane on each magnetic wall, which is similar to the magnetization rotation for low $|\vec{j}_{in}|$ below the threshold current density. The magnetic walls

Figure 3. (a) shows typical dynamics of $M_x$ at $|\vec{j}_{in}|$ above $j_c$. (b) and (c) show $x$-component of $\vec{S}_i$ on $x$-$z$ plane of the cross section including center of the nano-contact. The snap shots in (b) and (c) correspond to the maximum and minimum of $M_x$ indicated by (b) and (c) in (a), respectively. The dashed lines in (b) and (c) denote magnetic walls.
at different positions have different rotation velocities because the rotation velocities depend on values of the spin-transfer torque at positions of the magnetic walls[19]. Thus the irregular oscillation consists of several oscillation modes. In addition, the domain nucleation induces two of the oscillation modes and the domain annihilation cancels them. The irregular oscillation is due to the composite effect of the several oscillation modes and the domain nucleation-annihilation.

Here we discuss a voltage oscillation signal induced by the current-induced instability. The current-induced domain nucleation-annihilation oscillation induces a resistance oscillation because the resistance depends on the number of the magnetic walls[24]. However the current-induced instability does not occur in the experiment[9] by Suzuki et al. under dc current of the order of $10^9$ A/cm$^2$ less than $j_c \sim 10^{10}$ A/cm$^2$. On the other hand in other situations the current-induced instability appears under dc current of the order of $10^9$ A/cm$^2$, which is an upper limit of the current density in experiments. For example we point out that such the voltage oscillation signal is induced for the nano-contact made of a material with low exchange stiffness because the threshold current density decreases as the exchange stiffness decreases.

In conclusion we investigated dynamics of the geometrically confined magnetic wall under huge current by using a micromagnetic simulation technique in order to clarify the current-induced instability of the geometrically confined magnetic wall. We observed the domain nucleation-annihilation oscillation above a threshold current density. We pointed out the possibility of the voltage oscillation signal due to the current-induced instability for the nano-contact made of a material with a low exchange stiffness.

The authors thank M. Doi, H. Iwasaki, M. Ichimura, K. Miyake, M. Takagishi, M. Sahashi, H. Ohtori, T. Taniguchi, N. Yokoshi and K. Seki for useful discussions. The work was supported by NEDO and MEXT.Kakenhi(No.19740243 and No.18740226). This work was performed using facilities of the Institute for Solid State Physics, the University of Tokyo.

References
[1] Bruno P 1999 Phys. Rev. Lett. 83 2425
[2] van Gorkom R P, Brataas A and Bauer G E W 1999 Appl. Phys. Lett. 74 422
[3] Garcia N, Munoz M and Zhao Y W 1999 Phys. Rev. Lett. 82 2923
[4] Imamura H, Kobayashi N, Takahashi S and Maekawa S 1999 Phys. Rev. Lett. 84 1003
[5] Chopra H D, Sullivan M R, Armstrong J N and Hua S Z 2005 Nature materials 4 832–837
[6] Fuke H N, Hashimoto S, Takagishi M, Iwasaki H, Kawasaki S, Miyake K and Sahashi M 2007 IEEE Trans. Magn. 43 2848
[7] Takagishi M, Fuke H N, Hashimoto S, Iwasaki H, Kawasaki S, Shiozaki R and Sahashi M 2009 J. Appl. Phys. 105 07B725
[8] Sato J, Matsushita K and Imamura H 2009 J. Appl. Phys. 105 07D101
[9] Suzuki H, Endo H, Nakamura T, Tanaka T, Doi M, Hashimoto S, Fuke H N, Takagishi M, Iwasaki H and Sahashi M 2009 J. Appl. Phys. 105 07D124
[10] Slonczewski J C 1996 J. Magn. Magn. Mater. 159 159
[11] Slonczewski J C 1996 J. Magn. Magn. Mater. 261 L26
[12] Berger L 1996 Phys. Rev. B 54 9353
[13] Berger L 2001 J. Appl. Phys. 90 4632
[14] Bazaliy Y B, Jones B A and Zhang S C 1998 Phys. Rev. B 57 R3213
[15] Shibata J, Tatara G and Kohno H 2005 Phys. Rev. Lett. 94 076601
[16] Ohe J and Kramer B 2006 Phys. Rev. B 74 201305(R)
[17] Ohe J and Kramer B 2007 J. Mag. Mag. Mater. 310 2015
[18] He J and Zhang S 2008 Phys. Rev. B 78 012414
[19] Zhang S and Li Z 2004 Phys. Rev. Lett. 93 127204
[20] Shakespear K F, Perdue K L, Moyerman S M, Checkelsky J G, Harberger S S, Tamboli A C, Carey M J, Sparks P D and Eckert J C 2005 J. Appl. Phys. 97 10C513
[21] Zhang S, Levy P M and Fert A 2002 Phys. Rev. Lett. 88 236601
[22] Visscher B and Feng X 2002 Phys. Rev. B 65 104412
[23] Matsushita K, Sato J and Imamura H 2009 J. Appl. Phys. 105 07D525
[24] Dzero M, Gor’kov L P, Zvezdin A K and Zvezdin K A 2003 Phys. Rev. B 67 100402(R)