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Magnetization reversal of permalloy film by pure spin current injection: relation between reversal time and injected surface

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The dynamics of the magnetization reversal process in a nanosized permalloy film by the pure spin current (PSC) injection is analyzed. We have performed micromagnetic simulation based on the Landau-Lifshitz equation taking into account both the relaxation term and spin transfer torque term caused by the PSC. PSC is injected into the permalloy from a side of the film. We compare the magnetization reversal times among the PSCs injected from each of sides. The fast magnetization reversal occurs for the PSC injected from the side which area is smallest, i.e. highest spin current density, if we impose a condition that the intensity of the spin current is constant irrespective to the area of the side from which the PSC is injected.

KEYWORDS: Landau-Lifshitz equation, magnetization switching

1. Introduction

In a magnetic device or spintronics device such as a magnetoresistance element and a magnetic random access memory, a ferromagnet (FM) chip is used on a memory cell. It also need to control magnetization direction quickly in the cell with low power. Magnetization is usually controlled by a magnetic field or spin-transfer torque (STT) of a spin-polarized current [1, 2].

Magnetization reversal by injecting a pure spin current (PSC) is one of the methods of STT switching [3]. A PSC is generated by using a spin valve structure [4], which is a junction of a FM and a nonmagnetic metal. The PSC drifts into a target FM and the injected PSC decays in the FM. STT is developed around the injection side [5, 6] and the magnetization reverses. Recently, this magnetization reversal is demonstrated with the permalloy (Py) thin film [3].

The PSC can be injected from each of sides into the film because the generation FM can be set apart from the target FM. However, the relation between the side from which PSC is injected and the magnetization reversal is unclear. We study the relation by using the micro-magnetic simulation based on the Landau-Lifshit equation with the relaxation term and STT term of PSC in this paper.

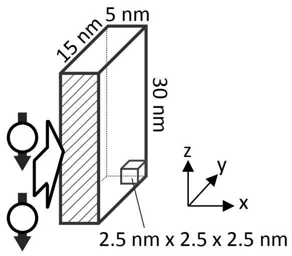

Fig. 1. Image of the PSC injection into the Py film from the middle area side. The large box of 5 nm × 15 nm × 30 nm is the film and the small box of 2.5 nm × 2.5 nm × 2.5 nm is one of the divided small cells. The small arrows and large arrow is the spin-polarization direction and current direction of the PSCs, respectively. The shaded sides of the large box is the side into which the PSC is injected.

2. Model and Methods

We simulated the magnetization reversal process in the small Py film by using the micro-magnetic simulation. The film is cuboid as depicted in figure 1 and the size of film was 5 nm × 15 nm × 30 nm, which was divided into the small cells of 2.5 nm × 2.5 nm × 2.5 nm. Magnetization of the film was reversed to –*z*-direction from +*z*-direction by injecting the PSC which spin-polarization is along –*z*-direction. The PSC was injected in three ways, namely injected from the top, front, and left sides of the film, which areas are 5 nm × 15 nm, 5 nm × 30 nm, and 15 nm × 30 nm, respectively. The schematic of the PSC injected from the front side into the film is shown in figure 1.

The magnetic moment (MM) in each small cell was solved by using the Landau-Lifshit (LL) equation with the STT term by the PSC [7 - 9], which is

$$\frac{\partial \boldsymbol{m}}{\partial t} = -|\gamma|\,\boldsymbol{m}\times\boldsymbol{H}_{\mathrm{eff}} - \alpha|\gamma|(\boldsymbol{m}\times(\boldsymbol{m}\times\boldsymbol{H}_{\mathrm{eff}})) - \frac{1}{M_{\mathrm{S}}}(\boldsymbol{m}\times(\boldsymbol{m}\times\nabla\boldsymbol{j}_{\mathrm{s}}))\,, \tag{1}$$

where $\boldsymbol{m}$ is a unit vector of the MM of each small cell, γ is the gyro-magnetic ratio of 1.76×10^7 rad/(s·Oe), $\boldsymbol{H}_{\mathrm{eff}}$ is a combination of static and exchange magnetic fields, α is the damping constant of 0.02, and $\boldsymbol{j}_{\mathrm{s}}$ is the PSC density, which is the tensor with spin-current vector and spin-polarization direction, and M_{S} is a saturated magnetization for the Py of 850 emu/cm^3. The exchange stiffness constant is 1.3×10^{-6} erg/cm for estimation of an exchange magnetic field.

We assumed that the PSC decays exponentially in the film, since the PSC is relaxed within several nanometers in Py films [10]. We introduced a quantity $u = |\boldsymbol{j}_{\mathrm{s}}|/M_{\mathrm{S}}$ which decays with a characteristic diffusion length λ of 4 nm as $u = u_0 \exp(-x/\lambda)$, where u and u_0 have a dimension of velocity, and x is the distance from the side of the film from which the PSC is injected. We call u_0 the injection velocity of the PSC. The PSCs were uniformly injected from each of sides. When the PSC is injected from the left side, the PSC does not fully decay in this model because the thickness of the film is close to the diffusion length. However, we assumed that the injected PSC did not move outside the film and fully decayed in the film forcibly.

The initial MMs at $t = 0$ were obtained by one nanosecond of relaxation from those originally oriented along +z-direction. The PSC injection began at $t = 0$ and then u_0 is kept constant for $t > 0$. We employed the injection time when the magnetization is mostly inverted to –z-direction, i.e. $\langle m_z \rangle = -0.95$, as the magnetization reversal time (t_{r}).

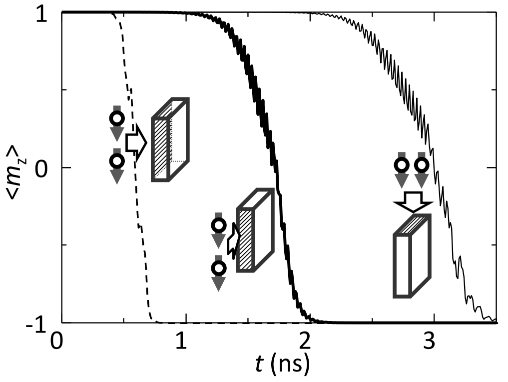

Fig. 2. Average of normalized magnetic moments during the magnetization reversal process in the film with the PSC injection. (a) The PSCs with u_0 = 100 m/s is injected into the film from the left side (broken curve), front side (bold solid curve), and top side (thin solid curve), respectively.

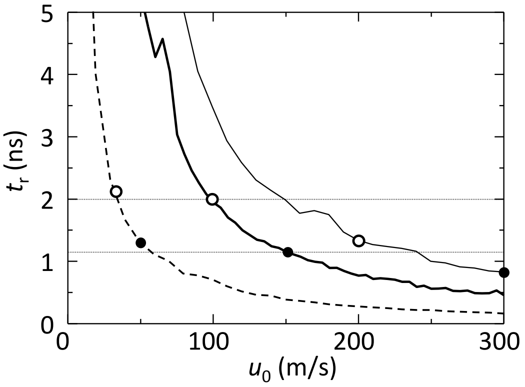

Fig. 3. Magnetization reversal time (t_r) as a function of the injection velocity (u_0). The PSC is injected from the left (broken curve), front (bold solid curve), and top small side (thin solid curve). The open and closed circles are obtained by the same intensity of PSCs injected from the front side with u_0 = 100 m/s and 150 m/s of the injection, respectively.

3. Results

First, we simulated the magnetization reversal process with injecting the PSC of u_0 = 100 m/s into the film from each of the sides. Figure 2 shows the *z*-component of averaged ***m*** (<m_z>) as a function of the injection time of the PSC (t). At the beginning, <m_z> changes little because the MMs hardly take STT from the PSC since the spin-polarization direction of the PSC is nearly anti-parallel to the MMs. STT of $\boldsymbol{m}\times(\boldsymbol{m}\times\nabla\boldsymbol{j}_s)$ increases with decreasing |<m_z>|, i.e. ***m*** is tilted from +z-direction, and magnetization dramatically decreases. Finally magnetization reversal occurred even though the PSC decayed around the injection edge. Magnetization reversed at 0.7 ns, 2.0 ns, and 3.4 ns for the PSC injected from the left, front, and top side of the film, respectively. The size of a film in which magnetization reversal can occurs was discussed in Ref [7]. [If we use a model of the PSC going through the film without decay, the magnetization reversal time is 0.9 ns for the PSC injected from the left side.]

We compare the magnetization reversal times for PSCs injected in three ways with the same injection velocity. Figure 3 shows the reversal time as a function of the injection velocity. The reversal time was decreased in approximately inversely proportion to the injection velocity. Magnetization reversal for the PSC injected from the left side is the fastest because the intensity of the PSC is the largest.

We compare the magnetization reversal times among three types of the injection for the same intensity of the PSC, i.e. the product of the injection velocity and injection area ($u_0 \times S$) is kept constant irrespective of the side. The ratio of the injection velocity estimated for the PSCs injected form the left (top) side to the front side is 1/3(2.0). The magnetization reversal times for the PSC injected from front side with u_0 = 100 m/s (150 m/s) are plotted as the open (closed) circles in figure 3. Magnetization is reversed

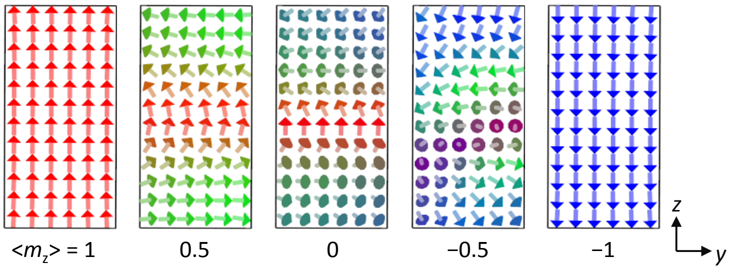

Fig. 4. (Color online) Snapshots of the magnetic moments in the film at $<m_z> \sim 1, 0.5, 0, -0.5$, and -1 during the magnetization reversal process. The PSC with $u_0 = 200$ m/s is injected from the top side of the film (the top side in this figure). Each arrow represents the direction of the magnetic moment on each of small cells.

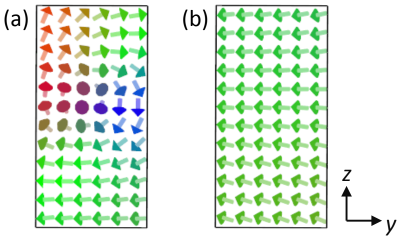

Fig. 5. (Color online) Snapshots of the magnetic moments in the film at $<m_z> \sim 0$ during the magnetization reversal process by injecting the PSC with (a) $u_0 = 100$ m/s from the front side of the film (the left side in this figure) and (b) $u_0 = 33.3$ m/s from the left side of the film (the front side in this figure).

at $t_r = 2.0$ ns (1.2 ns). The reversal times for the PSC injected from the other side are also plotted with the same marks in figure 3. We found that the magnetization reversal for the PSC injected from the top side is the fastest of $t_r = 1.3$ ns (0.84 ns), and that from the left side is the slowest of $t_r = 2.2$ ns (1.3 ns) even though the PSC is fully relaxed in the film.

Next, we introduce the snapshots of the MMs in the film during the magnetization reversal process which correspond to the results marked by the open circles in Figure 3. Figure 4 shows snapshots for the PSC injected from the top side with $u_0 = 200$ m/s. The PSC was injected from top side of the figure. At first, the MMs near the injection side rotated with STT of the PSC. The rotating MMs change the effective static fields and exchange fields for the around MMs. Especially, the exchange fields tilt the MMs same direction. Finally, magnetization is reversed.

We also show the snapshots of the MMs at $<m_z> \sim 0$ for the PSC injected from the front side with $u_0 = 100$ m/s and the left side with $u_0 = 33.3$ m/s in figure 5. During the injection from the front side, a small magnetic vortex was produced. However it depends whether a vortex or a magnetic wall was produced or the magnetization smoothly reverse. When the PSC was injected from the top side, the magnetization reverses with roughly uniform rotation of MMs. When magnetization is reversed with small spin injection velocity of $u_0 < 25$ m/s, all MMs rotate more uniformly during the magnetization reversal process for the PSCs injected from each of sides.

When the PSC with a larger spin injection velocity is injected, the rotation of MMs due to the STT of PSC is faster than these due to the external magnetic fields. And the MMs experience the larger magnetic fields produced from differences in the direction between the MMs. Hence, the rotations of the MMs accelerate. As a result, the faster magnetization reversal occurs.

3. Conclusion

The dynamics of the magnetization reversal process in the nanosized permalloy film by the pure spin current injection has been analyzed. The micro-magnetic simulation base on the on the Landau-Lifshit equation with the spin transfer torque term has been used. We have compared the magnetization reversal time among the PSCs injected from each of sides of the film. The fast magnetization reversal occurs for the PSC injected from the side which area is smallest, i.e. highest spin current density, if we impose a condition that the intensity of the spin current is constant irrespective to the area of the side from which the PSC is injected.

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