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Research articles

Thickness dependence of magnetization dynamics of an in-plane anisotropy ferromagnet under a crossed spin torque polarizer

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ABSTRACT

Magnetization dynamics of a soft layer (SL) with in-plane anisotropy and under a spin transfer torque (STT) from a perpendicularly magnetized reference layer is investigated. The thickness t of the SL is varied from 1 nm to 4 nm. It is found that uniform and damped oscillations of SL magnetization could be seen at both positive and negative applied current values. The range of each type of magnetization dynamics and the frequency values could be adjusted by changing the current density. The results obtained show the importance of optimizing the SL thickness in addition to its intrinsic properties for spin torque oscillator application with low applied current, high frequency and wide operation range.

1. Introduction

Under a polarized current, the magnetization of a ferromagnet could be reversed [1–11] or kept oscillating at a certain frequency [12–20]. This later feature could be used to build next generation microwave devices for information and communication technology. The basic structure of these devices, called spin torque oscillator (STO), is made of two ferromagnetic layers separated by a nonmagnetic spacer. The magnetically hard layer serves as a spin polarizer while the second one, magnetically soft, has its magnetization changeable under spin transfer torque (STT) [21,22]. The electrical signal relies on the measurement of the magnetoresistance of the device. STO based devices offer several advantages such as a wide range of frequency through the selection of materials properties, their geometry and DC-current magnitude. Also these devices could be used in harsh environment with high temperature and radiation.

Since the first experiment on STO, intensive investigations of materials with in-plane anisotropy were conducted. More recently, studies on magnetization dynamics of a soft layer under perpendicular anisotropy RL were carried out [23–26]. Firastrau et al. [27] reported macrospin and microspin results and Houssameddine et al. [28] experimentally demonstrated this geometry. The STO can be used as a single independent oscillator [29], coupled with another STO [30] or combined with a magnetic tunnel junction (MTJ) device [26]. The behaviour of coupled oscillators can be different from that of a single STO [31]. For these applications [26,29,30], it will be important to understand and control variations in frequencies of the spin torque oscillator, as a function of device geometry.

In this paper, the micromagnetic simulations were carried out to gain insight into the free layer thickness effect on the magnetization dynamics of a single STO device. This simulation study is to understand and tailor the design of a memory element wherein, a spin torque oscillator with an optimal frequency will be integrated with a conventional magnetic tunnel junction that could be the platform of future magnetic memory [26]. The study reveals that a sustainable uniform oscillation is possible for a limited range of applied current density which depends on the thickness of the magnetic layer. A detail discussion on magnetization dynamics for different conditions will be presented.

2. Theoretical model

A trilayer structure comprising a magnetic free layer (FL), a magnetic reference layer (RL) and a non-magnetic layer between them as shown in Fig. 1(a) was investigated. The magnetization direction of the FL ($\mathbf{m}$) can be changed under either a magnetic field or a polarized electric current while the direction of the RL magnetization ($\mathbf{m}_p$) is unchangeable and aligned in the z-direction. The object oriented micromagnetic framework (OOMMF) [32] with the public STT extension module [33] is used to numerically calculate the dynamics of the magnetization of the free layer in the presence of spin-polarized current by solving the Landau-Lifshitz-Gilbert equation with an additional Slonczewski-Berger spin-transfer term [21,22]

$$\frac{d\mathbf{m}}{dt} = -\gamma(\mathbf{m}\times\mathbf{H}_{\text{eff}}) + \alpha\left(\mathbf{m}\times\frac{d\mathbf{m}}{dt}\right) + \gamma\beta\varepsilon[\mathbf{m}\times(\mathbf{m}_p\times\mathbf{m})] \quad (1)$$

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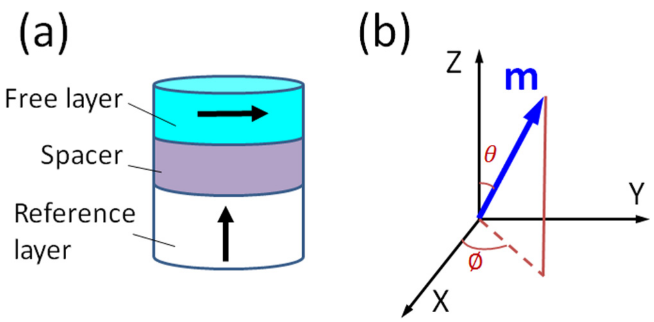

Fig. 1. (a) Schematic representations of the investigated device which is based on a magnetic free layer, and a magnetic reference layer separated by a non-magnetic layer and (b) the magnetization vector in spherical coordinates is also shown.

Where, γ and α are the gyromagnetic ratio and the Gilbert damping constant, respectively. The effective field $\mathbf{H}_{\text{eff}}$ is derived by minimizing the local energy densities and it includes the anisotropy field $\mathbf{H}_k$, the exchange field $\mathbf{H}_{ex}$ and the demagnetizing field $\mathbf{H}_d$.

$$\mathbf{H_{eff}} = \mathbf{H_k} + \mathbf{H_{ex}} + \mathbf{H_d} \tag{2}$$

In Eq. (1), $\mathbf{m}$ and $\mathbf{m}_p$ are the normalized magnetizations of the free and pinned layers, respectively. The parameter β can be expressed as:

$$\beta = \left|\frac{\hbar}{\mu_o e}\right| \frac{J}{tM_s}, \tag{3}$$

In the definition of β, e is the electron charge, J is current density, t is the free layer thickness, M_s is its saturation magnetization, μ_o is the permeability in free space and ħ is the reduced Planck constant. The spin-polarization efficiency ε is given by:

$$\varepsilon = \frac{P\Lambda^2}{(\Lambda^2+1) + (\Lambda^2-1)(\boldsymbol{m}\cdot\boldsymbol{m}_p)} \tag{4}$$

In Eq. (4), P is the spin-current polarization, ($\mathbf{m}\cdot\mathbf{m}_p$) is the relative angle between the magnetizations of free and reference layers, Λ is the asymmetry parameter [34]. The first term of Eq. (1) corresponds to the magnetization precession, the second term corresponds to damping, and the last term is the Slonczewski-Berger spin-transfer torque describing the interaction of the magnetization $\mathbf{m}$ with the spin polarized current traversing FL. We use the convention that a positive current flows from RL to FL. For this convention, positive current produces torque that tends to align $\mathbf{m}$ towards $\mathbf{m}_p$. In our calculation, the device with fixed diameter of 100 nm was divided by a cell of size $2 \times 2 \times t$ nm^3. The thickness t of the free layer was varied from 1 nm to 4 nm.

3. Results and discussions

We started with 1 nm thick free layer and the time dependence of the three components of its magnetization was plotted using the Object Oriented Micromagnetic Magnetic Framework [32]. The current-induced magnetization motions of only the free layer are considered, assuming that the RL magnetization is unaffected by DC current.

The magnetization vector for free layer **(m** = **M**/M$_s$ lies on the unit sphere) can be written in spherical coordinates as $\mathbf{m} = m_x\,\mathbf{i} + m_y\,\mathbf{j} + m_z\,\mathbf{k}$ where, $m_x = \sin\theta\cos\varphi$, $m_y = \sin\theta\sin\varphi$, $m_z = \cos\theta$, and (θ, φ) are the polar coordinates of the FL magnetization **m [**Fig. 1 (b)]. The z-component of magnetization m_z describes the amplitude of the excitation and is a non-oscillating quantity. It tilts towards positive and negative z-axis for positive current and negative current respectively as shown in Fig. 2(a) and (b). The x and y

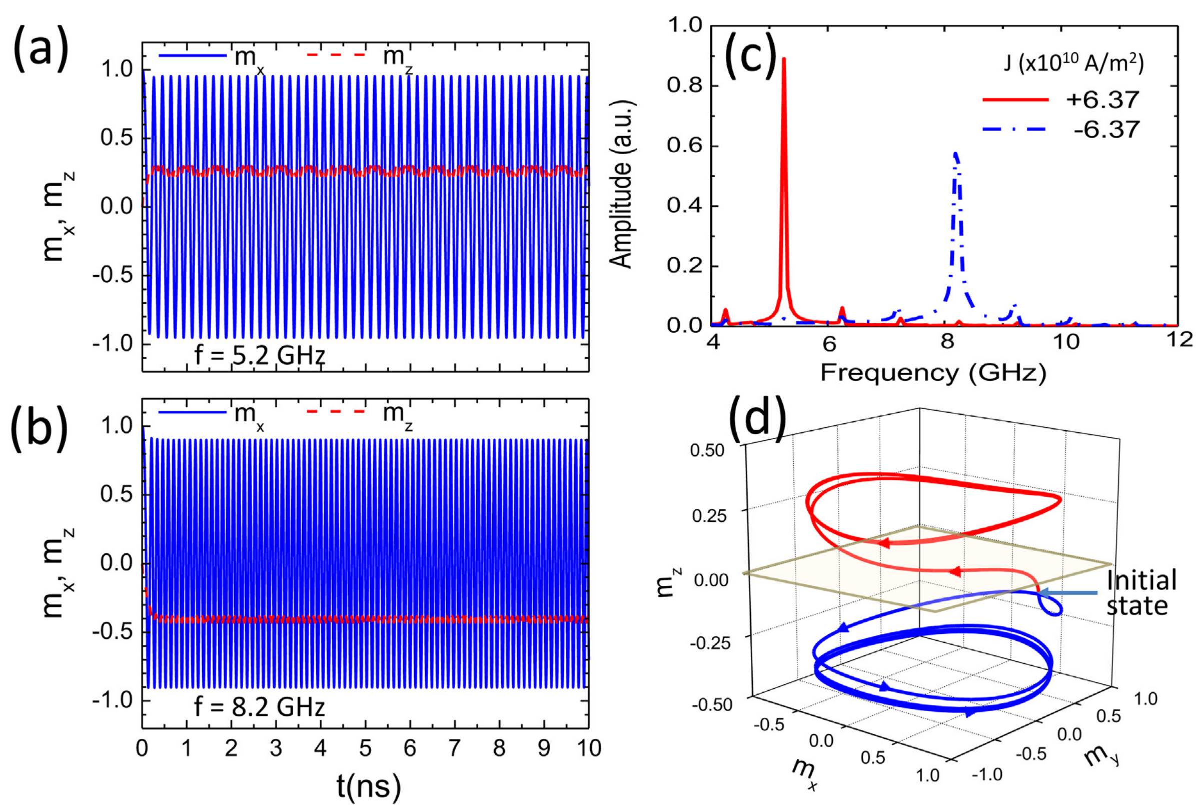

Fig. 2. Time dependence of the x and z components of the free layer magnetization for (a) J = +6.37 × 10^{10} A/m^2 and (b) J = −6.37 × 10^{10} A/m^2, (c) is a plot of the fast Fourier transform (FFT) of m$_x$ component of the full 16 ns long time trace and (d) is clockwise (red) and anticlockwise (blue) trajectory of normalized magnetization vector for the positive and negative current density, respectively. The saturation magnetization and anisotropy energy were fixed to 600 kA/m and 1 × 10^4 J/m^3, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)