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Effect of Biquadratic Coupling on Current Induced Magnetization Switching in Co/Cu/Ni-Fe Nanopillar

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Abstract. The effect of biquadratic coupling on spin current induced magnetization switching in a Co/Cu/Ni-Fe nanopillar device is investigated by solving the free layer magnetization switching dynamics governed by the Landau-Lifshitz-Gilbert-Slonczewski (LLGS) equation. The LLGS equation is numerically solved by using Runge-Kutta fourth order procedure for an applied current density of $5 \times 10^{12}\mathrm{Am}^{-2}$. Presence of biquadratic coupling in the ferromagnetic layers reduces the magnetization switching time of the nanopillar device from 61 ps to 49 ps.

Keywords: Spintronics, magnetization switching, nanopillar, spin transfer torque.
PACS: 75.78.Jp, 75.78.-n, 72.25.-b, 72.25.Mk, 85.75.-d

INTRODUCTION

Spin current induced magnetization switching in multilayers proposed by Slonczeswki [1] and Berger [2] have attracted much interest in recent years because of its potential applications in microwave frequency generators, read/write heads, spin transfer torque random access memories(STTRAM) and etc [3]. The speed of magnetization switching in magnetic multilayer is an important issue to develop potential applications. Growing multilayer nanopillar in an ideal layer by layer fashion is very difficult task. The resultant multilayers have certain interface roughness or discontinuities. There are two different coupling mechanisms, which arises due to the roughness of the layers [4]. First one is, orange peel coupling or Néel coupling arises in situations where the spacer layer has a uniform thickness with correlated roughness [5]. Second one is biquadratic coupling which occurs when the roughness of the free and pinned layers are uncorrelated [6]. The biquadratic coupling energy favours the perpendicular alignment of the free and pinned layers magnetization [4] and hence it is expected to reduce the switching time. We have recently studied the impact of orange peel coupling on spin current induced magnetization switching in a Co/Cu/Ni-Fe nanopillar device [7]. In the present paper, we investigate the impact of biquadratic coupling on magnetization switching time in the Co/Cu/Ni-Fe nanopillar. This can be done by solving the magnetization switching dynamics of the free layer governed by LLGS equation. The paper is organized as follows. In the following section, geometry of the Co/Cu/Ni-Fe nanopillar taken for our study is described and the dynamical equation (LLGS equation) expressing the switching dynamics of the free layer magnetization is constructed. In the results and discussion section, LLGS equation is numerically solved and the results are discussed.

MODEL AND DYNAMICAL EQUATION

The nanopillar considered for study has two ferromagnetic layers (Co, Ni-Fe) sandwiched by a nonmagnetic (Cu) spacer layer and the schematic sketch of the nanopillar is shown in FIGURE 1. The bottom ferromagnetic layer is made up of Cobalt (Co) and it is supposed to have periodic interfacial terraces with a period L and a height δ and it is called as pinned layer because of its magnetization is pinned along easy axis (along x-direction). The middle spacer layer is made by a non-magnetic metal Copper (Cu) with a thickness of 2 nm. Single domain ferromagnetic free

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layer is made up of low coercivity material Permalloy

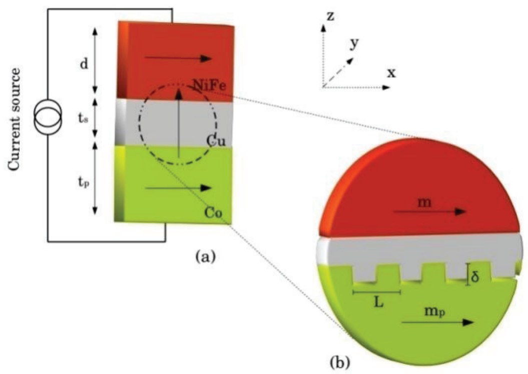

FIGURE 1. (a). A sketch of the Co/Cu/Ni-Fe nanopillar device. (b). In the zoomed view, we see the pinned layer (Co) have periodic interfacial terraces with a period L and a height δ.

(Ni-Fe) with a thickness of 4 nm. Ni-Fe layer is assumed to have smooth interface and its magnetization is free to move when the current is applied. The current is applied normal to the plane of the nanopillar (along z-direction) and it becomes spin polarized when the applied current passes through the pinned layer. The spin polarized electrons entered into the free layer via spacer layer produces a torque due to change in the electrons spin angular momentum. This torque is called as spin transfer torque which switches the magnetization of the free layer when the applied current is above the threshold value. The switching dynamics of the free layer magnetization is governed by the LLGS equation and it can be written in dimensionless form as,

$$\frac{d\boldsymbol{m}}{d\tau} = -(\boldsymbol{m} \times \boldsymbol{h}_{eff}) - \alpha[\boldsymbol{m} \times (\boldsymbol{m} \times \boldsymbol{h}_{eff})] + a_j[\boldsymbol{m} \times (\boldsymbol{m} \times \boldsymbol{m}_p)], \quad (1a)$$

$$\boldsymbol{m}^2 = \boldsymbol{m}^{x2} + \boldsymbol{m}^{y2} + \boldsymbol{m}^{z2} = 1. \quad (1b)$$

Where, α is the Gilbert damping parameter, $a_j = \frac{pJ\hbar}{\mu_0 ed M_s^2}$ is the spin transfer torque coefficient. Here, p is the polarization factor, J is the current density applied, μ_0 is the permeability of the free space, e is the electron's charge, d is the thickness of the free layer, $\mathbf{m}=\frac{\boldsymbol{M}}{M_s}$ is the normalized magnetization vector of the free layer, $\boldsymbol{m}_p$ is the normalized unit magnetization of the pinned layer, M_s is saturation magnetization of the Ni-Fe free layer and $\tau = \gamma M_s t$ is the dimensionless time, where γ is gyromagnetic ratio. $\boldsymbol{h}_{eff}$ is the effective magnetic field acting on the free layer and it can be written as,

$$\boldsymbol{h}_{eff} = \boldsymbol{h}_{ma} + \boldsymbol{h}_{shape} + \boldsymbol{h}_{ext} + \boldsymbol{h}_{bqc}. \quad (2)$$

Where, $\boldsymbol{h}_{ma}$ is the field term due to magneto-crystalline anisotropy. Our free layer has in-plane magnetization aligned along its easy axis (x-axis) and hence magneto-crystalline anisotropy field is, $\boldsymbol{h}_{ma} = h_a \boldsymbol{m}^x \boldsymbol{e}^x$, where $\boldsymbol{e}^x$ is the unit vector along x-direction and $h_a = \frac{2\boldsymbol{k}_a}{\mu_0 \boldsymbol{M}_s^2}$. Here, k_a is the magneto-crystalline anisotropy coefficient. $\boldsymbol{h}_{shape}$ is the field term corresponding to the shape anisotropy. In our case, the free layer lies in the xy-plane and hence the value of demagnetization factors becomes, $N_x=N_y=0$, and $N_z=1$. Therefore, shape anisotropy field can be written as, $\boldsymbol{h}_{shape} = -N_z m^z \boldsymbol{e}^{\boldsymbol{z}}$, where $\boldsymbol{e}^{\boldsymbol{z}}$ is the unit vector along z-direction. When an external magnetic field h_e is applied perpendicular to the easy axis (along y-direction), then $\boldsymbol{h}_{ext}=h_e\boldsymbol{e}^y$. There are uncompensated magnetic poles present in the edges of the pinned layer due to the roughness and they give rise to a magnetic dipole field in the direction of pinned layer magnetization (x-direction) [6]. The magnetic dipole field couples to the magnetization of the free layer and it is called as biquadratic coupling filed written as, $h_{bqc} = h_b m^x \boldsymbol{e}^{\boldsymbol{x}}$, where

$$h_b = \frac{\mu_0 M_s^2 \delta^2 L}{2\pi^3 A_{ex} d} \exp\left(\frac{-4\pi t_s}{L}\right)\left[1 - exp\left(\frac{-8\pi d}{L}\right)\right],$$

h_b is the magnitude of the biquadratic coupling strength. Here, δ and L are height and period of the roughness of the pinned layer respectively. A_{ex} is the exchange stiffness constant of the free layer and t_s is the thickness of the spacer layer. The total effective magnetic field acting on the free layer can be written as,

$$\boldsymbol{h}_{eff} = (h_a + h_b) m^x \boldsymbol{e}^{\boldsymbol{x}} + h_e\, \boldsymbol{e}^{\boldsymbol{y}} - N_z m^z \boldsymbol{e}^{\boldsymbol{z}}. \quad (3)$$

By substituting the effective field found in Eq. (3) into Eq. (1), we obtain the dynamical equation (LLGS equation) for our study. Solving of LLGS equation and the results are discussed in the forthcoming section.

RESULTS AND DISCUSSION

The magnetization switching dynamics of the free layer governed by the LLGS equation (eq. (1)) is numerically integrated using Runge-Kutta fourth order procedure in the presence and in the absence of biquadratic coupling separately. The material parameters used for the numerical simulation is shown in TABLE 1. Initially the free layer magnetization (**m**) is aligned along the positive x-direction. The applied current switches the magnetization into negative x-direction and time taken for this is called as switching time. Magnetization switching time of the free layer in the absence of biquadratic coupling is 61 ps for an applied current density of 5×10^{12} Am^{-2}. The presence of biquadratic coupling reduces the switching time from 61 ps to 49 ps (shown in FIGURE 2). The reason is that, biquadratic coupling favours the perpendicular alignment of the free and pinned layers magnetization,

TABLE 1. Values of various parameters used in the numerical simulations [7].

Parameter	Value
Polarization factor (p)	0.4
Gilbert damping parameter (α)	0.001
Saturation magnetization of Ni-Fe(Ms)	795 kAm^{-1}
Height of the roughness (δ)	0.8 nm
Wavelength of roughness (L)	40 nm
Exchange stiffness constant of Ni-Fe (A_{ex})	2.1×10^{-11} Jm^{-1}

and hence biquadratic coupling field moves magnetization of the free layer from in-plane to out of plane very fast. This generates a demagnetizing field which forces the magnetization of the free layer from out of plane into the plane (switched state). Thus biquadratic coupling field reduces the switching time. Since, biquadratic coupling occurs due to the roughness in the pinned layer, we study the impact of period of roughness on switching time.

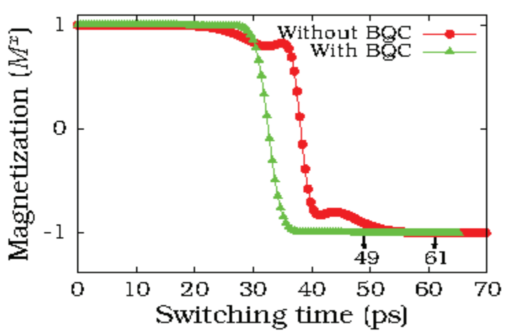

FIGURE 2. A plot of free layer magnetization versus switching time in the presence and in the absence of the biquadratic coupling (BQC).

We have varied the period of the roughness (interfacial terraces) from 0 nm to 70 nm and again solved the LLGS equation numerically for an applied current density of J = 5×10^{12} Am^{-2}. The data obtained are plotted in FIGURE 3. Magnetization switching time is 61 ps, when the period of the roughness is zero i.e. in the absence of biquadratic coupling. When the period of the roughness increases, number of uncompensated magnetic poles in the pinned layer increases, and it increases the biquadratic coupling field. Increase in the biquadratic coupling field fasten the magnetization switching and reduces the switching time (as shown in FIGURE 3). For the period of roughness of our device (40 nm), the switching time is 49 ps which agrees perfectly with the result in the FIGURE 2. Thus switching time can be reduced by making the nanopillar with biquadratic coupling.

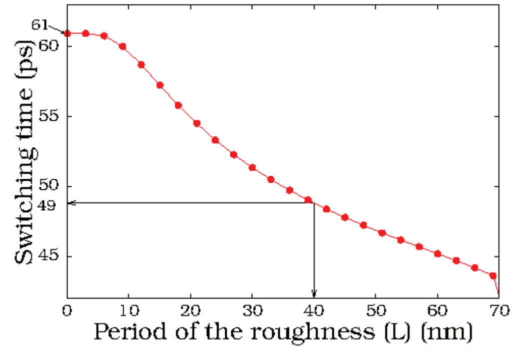

FIGURE 3. A plot of the period of the roughness versus switching for J = $5\times10^{12}Am^{-2}$.

CONCLUSION

The spin current induced magnetization switching in a Co/Cu/Ni-Fe nanopillar with biquadratic coupling is investigated by numerically solving the governing equation (LLGS equation). Magnetization switching time in the absence of biquadratic coupling is 61 ps and in the presence of biquadratic coupling it reduces to 49 ps. Also, the period of roughness effect on switching time confirms the presence of biquadratic coupling reduces the switching time. Fast magnetization switching can be achieved by constructing the nanopillar with biquadratic coupling.

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