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Impact of Biquadratic Coupling on Critical Current Density in Co/Cu/Ni-Fe Nanopillar

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Abstract. We have studied the effect of biquadratic coupling (BQC) on critical current density in the Co/Cu/Ni-Fe nanopillar by solving the magnetization switching dynamics of the free layer which is governed by Landau- Lifshitz-Gilbert-Slonczewski (LLGS) equation. The LLGS equation is analytically solved for the time independent case and value of the critical current density required to initiate the magnetization switching is calculated. Its value in the absence of BQC is $0.8576 \times 10^{12} Am^{-2}$ and in the presence of BQC its value increases to $1.0914 \times 10^{12} Am^{-2}$. BQC field is acting along the easy axis which opposes the free layer magnetization moving to the out of plane and hence the value of critical current density is high in the presence of BQC. We can reduce the critical current density by reducing the BQC field which can be achieved by making the nanopillar with minimal or no roughness in the pinned and free layer.

INTRODUCTION

Spin transfer torque magnetization switching in magnetic nanopillar devices is predicted by Slonczewski [1] and Berger [2] independently, have found applications in high density read heads, microwave frequency generators, and nonvolatile magnetic random access memories [3]. The reduction of the critical density is one of the key issues to develop memory applications. Growing ideal multilayer nanopillar without roughness is very difficult task. The resultant multilayers have certain interface roughness and they give rise to two different coupling mechanisms [4]. First one is orange peel coupling which arises in situations where the spacer layer has a correlated roughness. Second one is biquadratic coupling (BQC) which occurs when the roughness of the free and pinned layers are uncorrelated [5]. Recently we have studied the impact of orange peel coupling on spin current induced magnetization switching [6]. In this work, we investigate the impact of biquadratic coupling on critical current density in the Co/Cu/Ni-Fe nanopillar device. This can be done by analytically solving the magnetization switching dynamics of the free layer governed by LLGS equation. The paper is structured as follows. Geometry of the Co/Cu/Ni-Fe nanopillar and the dynamical equation (LLGS equation) expressing the switching dynamics of the free layer magnetization is described in the forthcoming section. In the critical current density for magnetization switching section, value of the critical current density is analytically calculated in the presence and in the absence of BQC and the results are discussed. Finally results are concluded in the conclusion section.

MODEL AND DYNAMICAL EQUATION

The Co/Cu/Ni-Fe nanopillar is considered for our study in this paper and it consists of two ferromagnetic layer (Co, Ni-Fe) sandwiched by a nonmagnetic (Cu) spacer layer. Geometry of the above nanopillar device is shown in the FIGURE 1. The ferromagnetic Cobalt (Co) layer with a thickness of 4 nm possessing high coercivity, whose

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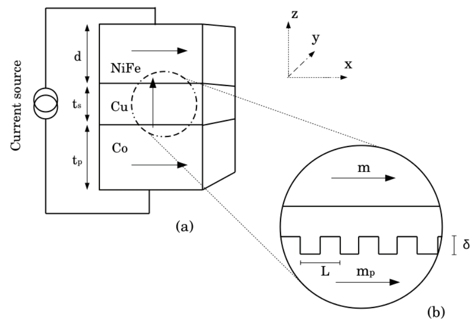

FIGURE 1. (a). Geometry of the Co/Cu/Ni-Fe nanopillar device. (b). In the zoomed view, we see the pinned layer (Co) have periodic interfacial terraces with a period L and a height δ.

magnetization ($\mathbf{m_p}$) is pinned and lies parallel to the plane of the layer (x-direction) forms the pinned layer and it is supposed to have periodic interfacial terraces with a period L and a height δ. The middle spacer layer is made up of the nonmagnetic metal Copper (Cu) with a thickness (2 nm). Free layer is made up of a low coercivity material Permalloy (Ni-Fe) and its thickness is 4 nm. Free layer is assumed to have smooth interface and it have in-plane magnetization which is free to move when the current is applied. Current is applied along z-direction of the nanopillar device and it becomes polarized when passing through the pinned layer. Spin polarized current entered into the free layer produces a torque due to the exchange of angular momentum between a spin polarized current and the magnetization of the free layer. When the applied current is above the critical value, spin transfer torque will switch the magnetization of the free layer. The free layer magnetization switching dynamics is governed by the LLGS equation and it can be written in dimensionless form as,

$$\frac{d\mathbf{m}}{d\tau} = -(\mathbf{m}\times\mathbf{h}_{eff}) - \alpha[\mathbf{m}\times(\mathbf{m}\times\mathbf{h}_{eff})] + a_j[\mathbf{m}\times(\mathbf{m}\times\mathbf{m}_p)], \qquad \text{and} \qquad \mathbf{m}^2 = m^{x^2} + m^{y^2} + m^{z^2} = 1. \quad (1)$$

Here, $\mathbf{m} = (m^x, m^y, m^z)$ represents the magnetization of the free layer. $\tau = \gamma M_s t$ is the dimensionless time. Where γ is the gyromagnetic ratio and M_s is the saturation magnetization of the free layer. α is Gilbert damping parameter and $a_j = \frac{pJ\hbar}{\mu_0 ed M_s^2}$ is the spin transfer torque coefficient. The current flows from the pinned layer to the free layer, and so positive value is assigned to the spin transfer coefficient a_j in Eq. (1). p is the polarization factor, J is the current density applied from the source, $\hbar$ is the reduced Planck's constant, μ_0 is the permeability of free space, e is the electron's charge and d is the thickness of the free layer. $\mathbf{m}_p$ represents the unit magnetization vector of the pinned layer. $\mathbf{h}_{eff}$ is the total effective magnetic field acting on the free layer and it can be written as,

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

The free layer has in-plane magneto-crystalline anisotropy and it aligned along easy axis(x-direction). Hence the field contribution due to the magneto-crystalline anisotropy is written as $\mathbf{h}_{ma} = h_a m^x \mathbf{e}^x$, where $h_a = \frac{2k_a}{\mu_0 M_s^2}$, here k_a is the magneto-crystalline anisotropy coefficient. $\mathbf{e}^x$ is the unit vector along x-direction. Shape anisotropy arises due to the demagnetizing field and the field contribution due to shape anisotropy is written as $\mathbf{h}_{shape} = -[N_x m^x \mathbf{e}^x + N_y m^y \mathbf{e}^y + N_z m^z \mathbf{e}^z]$, where N_x, N_y, N_z are the demagnetization factors, and $\mathbf{e}^x, \mathbf{e}^y, \mathbf{e}^z$ represent the unit vectors along x, y and z directions respectively. The value of the demagnetization factors depends upon the shape of the material. Since, the free layer lies in the xy-plane, $N_x = N_y = 0$ and $N_z = 1$. Therefore, field term due to shape anisotropy becomes $\mathbf{h}_{shape} = -N_z m^z \mathbf{e}^z$. When an external magnetic field h_e is applied perpendicular to the easy axis (y-direction), the term due to the external field can be written as $\mathbf{h}_{ext} = h_e \mathbf{e}^y$. 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). This magnetic dipole field couples with the magnetization of the free layer and it is called as biquadratic coupling filed which can be written as, $\mathbf{h}_{bqc} = h_b m^x \mathbf{e}^x$, where $h_b = \frac{\mu_0 M_s^2 \delta^2 L}{2\pi^3 A_{ex} d} \exp\left(\frac{-4\pi t_s}{L}\right)\left[1 - \exp\frac{-8\pi d}{L}\right]$, h_b is the magnitude of the 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 Cu layer. Therefore, the total effective magnetic field acting on the free layer can be written as,

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

By substituting the effective field (eq. 3) and value of $\mathbf{m}_p$ into the Eq. (1), we get the dynamical equation(LLGS equation) as,

$$\frac{d\mathbf{m}}{d\tau} = -[\mathbf{m}\times((h_a + h_b)m^x\mathbf{e}^x + h_e\mathbf{e}^y - N_z m^z\mathbf{e}^z)] - \alpha[\mathbf{m}\times(\mathbf{m}\times((h_a + h_b)m^x\mathbf{e}^x + h_e\mathbf{e}^y - N_z m^z\mathbf{e}^z))] + a_j[\mathbf{m}\times(\mathbf{m}\times\mathbf{e}^x)]. \quad (4)$$

By analytically solving the LLGS equation (4), we can calculate the value of critical current density required to initiate the switching of the magnetization of the free layer and it is discussed in the next section.

CRITICAL CURRENT DENSITY FOR MAGNETIZATION SWITCHING

The critical value of the current density can be calculated from the time independent solution of the LLGS equation (4). In the static limit ($\frac{dm}{dt} = 0$), the damping term ($\mathbf{m} \times \frac{d\mathbf{m}}{dt}$) vanishes. To obtain the time independent solution of the LLGS equation, we write the LLGS equation(4) in the component form for the static case as,

$$(h_e + N_z m^y)m^z - a_j(m^{y^2} + m^{z^2}) = 0, \quad (5)$$

$$-(h_a + h_b + N_z)m^x m^z + a_j m^x m^y = 0, \quad (6)$$

$$(h_a + h_b)m^x m^y - h_e m^x + a_j m^x m^z = 0. \quad (7)$$

Solving Eqs. (6) and (7) algebraically, the time independent solution for m^y is obtained as

$$m^y = \frac{h_e(h_a + h_b + N_z)}{a_j^2 + (h_a + h_b)(h_a + h_b + N_z)}. \quad (8)$$

The time independent solution of m^z can be obtained by substituting the value of m^y found in Eq. (8) into Eq. (6) as

$$m^z = \frac{h_e a_j}{a_j^2 + (h_a + h_b)(h_a + h_b + N_z)}. \quad (9)$$

The time independent solution of m^x is obtained by substituting the values of m^y and m^z in the length constraint equation ($\mathbf{m}^2 = m^{x^2} + m^{y^2} + m^{z^2} = 1$). The resultant solution reads

$$m^x = \left[1 - \frac{h_e^2[a_j^2 + (h_a + h_b + N_z)^2]}{[a_j^2 + (h_a + h_b)(h_a + h_b + N_z)]^2}\right]^{\frac{1}{2}}. \quad (10)$$

The critical current density for magnetization switching is obtained by using the time independent solutions given in Eqs. (8-10) as initial conditions. The free layer magnetization is initially aligned along the easy axis, i.e. along x-direction, so that the initial conditions are $m^x = 1$, $m^y = 0$ and $m^z = 0$. If the free layer magnetization satisfies the above initial conditions, then the magnetization switching can occur when the value of m^x becomes zero. i.e. when,

$$h_e^2[a_j^2 + (h_a + h_b + N_z)^2] = [a_j^2 + (h_a + h_b)(h_a + h_b + N_z)]^2. \quad (11)$$

Using the above condition (Eq. (11)) and switching off the external applied field ($h_e = 0$), we get a_j^2 as,

$$a_j^2 = -(h_a + h_b)(h_a + h_b + N_z). \quad (12)$$

By substituting the value of $a_j (a_j = \frac{pJ\hbar}{\mu_0 e d M_s^2})$ into Eq. (12), the expression for the critical current density J_c in the presence of BQC is obtained as

$$J_c = \left(\frac{\mu_0 e d M_s^2}{p\hbar}\right)[(h_a + h_b)(h_a + h_b + N_z)]^{\frac{1}{2}}. \quad (13)$$

The above equation shows that the critical current density depends on the thickness of the free layer(d), magnetocrystalline anisotropy(h_a), shape anisotropy(N_z) and the BQC(h_b). The actual value of the critical current density required to initiate the switching of the magnetization of the Permalloy free layer is calculated from Eq. (13) by

TABLE 1. Values of various parameters used in the calculations [6].

Parameter	Symbol	Value
Polarization factor	p	0.4
Gilbert damping parameter	α	0.001
Magnetocrystalline anisotropy coefficient of Ni-Fe	k_a	$2 \times 10^3 Jm^{-3}$
Saturation magnetization of Ni-Fe	M_s	$0.795 \times 10^6 Am^{-1}$
Height of the roughness of the pinned layer	δ	$0.8 \times 10^{-9} m$
Period of the roughness of the pinned layer	λ	$40 \times 10^{-9} m$

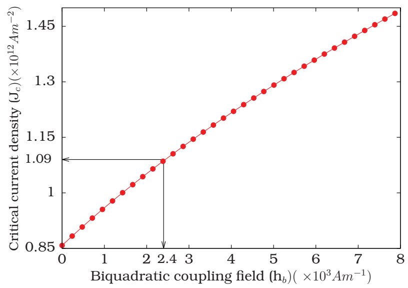

FIGURE 2. A plot of the biquadratic coupling field versus critical current density.

substituting the values of all the respective experimental parameters found in TABLE 1. The resultant value of the critical current density in the presence of the BQC is $1.0914 \times 10^{12} Am^{-2}$ and in the absence of BQC ($h_b = 0$) its value decreases to $0.8576 \times 10^{12} Am^{-2}$. BQC field is acting along the easy axis which opposes the free layer magnetization moving to the out of plane and hence the value of critical current density is high in the presence of BQC. We can reduce the critical current density by reducing the BQC field (as shown in FIGURE 2) which can be achieved by making the nanopillar with minimal or no roughness in the pinned and free layer. When the roughness decreases, number of uncompensated magnetic poles present in the pinned layer decreases, and it reduces the BQC field.

CONCLUSION

Effect of BQC on critical current density in the Co/Cu/Ni-Fe nanopillar is studied by analytically solving the LLGS equation. Value of the critical current density required to initiate the magnetization switching in the absence of BQC is $0.8576 \times 10^{12} Am^{-2}$ and in the presence of BQC its value increases to $1.0914 \times 10^{12} Am^{-2}$. By making the nanopillar with minimal or no roughness in the pinned and free layer, we can reduce the critical current density.

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