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

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Introduction

- Spin transfer torque magnetization switching in magnetic nanopillar devices have found applications in high density read heads, microwave frequency generators, and non-volatile magnetic random access memories.
- The reduction of the critical current 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.
- 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.
- In this work, we investigate the impact of biquadratic coupling on critical current density in the Co/Cu/Ni-Fe nanopillar device.

Geometry of the Co/Cu/Ni-Fe Nanopillar

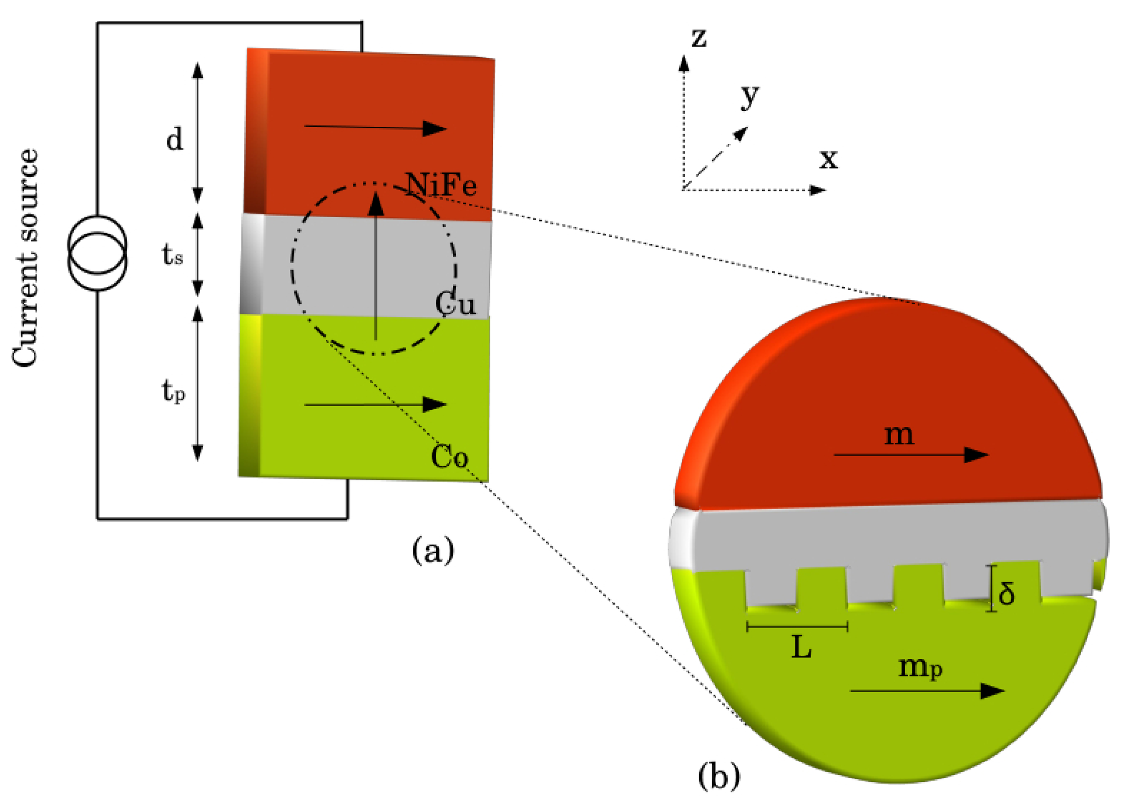

Fig. 1: (a). Geometry of the Co/Cu/Ni-Fe nanopillar device. (b). In the zoomed view, we see the pinned layer (Co) have periodic interfacial terraces with a period L and a height δ.

Dynamical Equation

The magnetization switching dynamics of the free layer in the Co/Cu/Ni-Fe nanopillar is governed by the Landau-Lifshitz-Gilbert-Slonczewski(LLGS) equation & it can be written as,

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

$$\mathbf{m} = (m^x, m^y, m^z), \qquad \mathbf{m}^2 = m^{x^2} + m^{y^2} + m^{z^2} = 1. \quad (1b)$$

Where, $\tau = \gamma M_s t$, $\quad a_j = \frac{pJ\hbar}{\mu_0 e d M_s^2}$

Effective field acting on the free layer

Total Effective Field : $\mathbf{h}_{eff} = \mathbf{h}_{ma} + \mathbf{h}_{shape} + \mathbf{h}_{ext} + \mathbf{h}_{bqc}$.

Magnetocrystalline Anisotropy : $\mathbf{h}_{ma} = h_a m^x \mathbf{e}^x$

Shape Anisotropy : $\mathbf{h}_{shape} = -(N_x m^x \mathbf{e}^x + N_y m^y \mathbf{e}^y + N_z m^z \mathbf{e}^z)$

External Magnetic Field : $\mathbf{h}_{ext} = h_e \mathbf{e}^y$

Biquadratic coupling filed : $\mathbf{h}_{bqc} == h_b m^x \mathbf{e}^x$

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

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

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.
- we write the LLGS equation(1) in the component form for the static case as,

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

$$-(h_a + h_b + N_z)m^x m^z + a_j m^x m^y = 0, \quad (3)$$

$$(h_a + h_b)m^x m^y - h_e m^x + a_j m^x m^z = 0. \quad (4)$$

- Solving Eqs. (2 - 4) algebraically, the time independent solution for m^x, m^y & m^z are obtained as

$$m^y = \frac{h_e(h_a + h_b + N_z)}{a_j^2 + (h_a + h_b)(h_a + h_b + N_z)}. \quad (5)$$

$$m^z = \frac{h_e a_j}{a_j^2 + (h_a + h_b)(h_a + h_b + N_z)}. \quad (6)$$

$$m^x = \left[1 - \frac{h_e^2[a_j^2 + (h_a + h_b + N_z)^2]}{[a_j^2 + (h_a + h_b)(h_a + h_b + N_z)]^2}\right]^{\frac{1}{2}}. \quad (7)$$

- 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,

$$h_e^2[a_j^2 + (h_a + h_b + N_z)^2] = [a_j^2 + (h_a + h_b)(h_a + h_b + N_z)]^2. \quad (8)$$

- If $h_e = 0$, we get a_j^2 as,

$$a_j^2 = -(h_a + h_b)(h_a + h_b + N_z). \quad (9)$$

- The expression for the critical current density J_c in the presence of biquadratic coupling is obtained as

$$J_c = \left(\frac{\mu_0 e d M_s^2}{p\hbar}\right)[(h_a + h_b)(h_a + h_b + N_z)]^{\frac{1}{2}}. \quad (10)$$

Values of various parameters

Parameters	Symbol	Value
Polarization factor	p	0.4
Gilbert damping parameter	α	0.001
Magnetocrystalline anisotropy coefficient of Ni-Fe	k_a	$2\times10^3 Jm^{-3}$
Saturation magnetization of Ni-Fe	M_s	$0.795\times10^6 Am^{-1}$
Thickness of the free layer (Ni-Fe)	d	$4\times10^{-9} m$
Thickness of the spacer layer (Cu)	t_s	$2\times10^{-9} m$
Height of the roughness of the pinned layer	δ	$0.8\times10^{-9} m$
Period of the roughness of the pinned layer	λ	$40\times10^{-9} m$

Table: Values of various parameters used in the calculations.

- The critical current density in the presence of the biquadratic coupling is $1.0914\times10^{12} Am^{-2}$.
- The critical current density in the absence of the biquadratic coupling is $0.8576\times10^{12} Am^{-2}$.

Conclusions

- Effect of biquadratic coupling on critical current density in the Co/Cu/Ni-Fe nanopillar is studied by analytically solving the Landau-Lifshitz-Gilbert-Slonczewski (LLGS) equation.
- Value of the critical current density required to initiate the magnetization switching in the absence of BQC is $0.8576\times10^{12} Am^{-2}$ and in the presence of BQC its value increases to $1.0914\times10^{12} Am^{-2}$.
- 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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