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

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Outline of Talk

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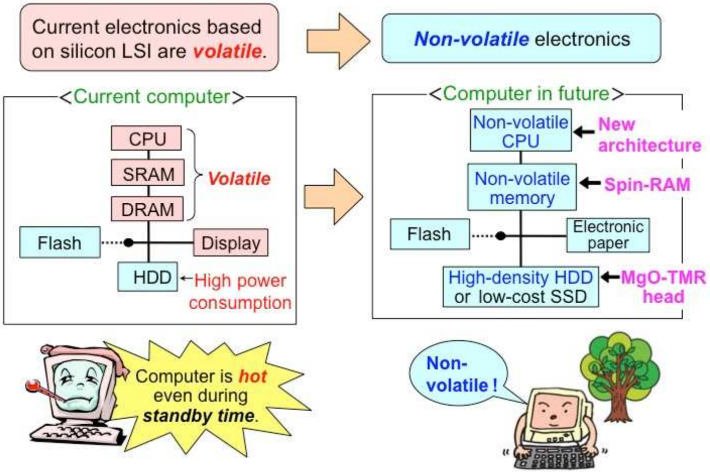
1. Introduction
2. Types of magnetization switching
3. Impact of biquadratic coupling on magnetization switching
4. Conclusion

Why We Study Current Induced Magnetization Switching?



Introduction

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- Data writing and reading process in hard disk and Magnetic Random Access Memory (MRAM) involves the switching of magnetization of the magnetic material which is in the form of nanofilms and nanopillars.

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- Data writing and reading process in hard disk and Magnetic Random Access Memory (MRAM) involves the switching of magnetization of the magnetic material which is in the form of nanofilms and nanopillars.
- By reducing the switching time, we can increase the data writing and reading speed.

Types of Magnetization Switching

Methods

1. Conventional or Stoner-Wohlfarth (SW) Switching.
2. Precessional Switching.

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Conventional or Stoner-Wohlfarth (SW) Switching

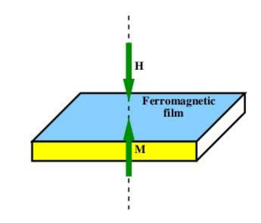

Figure : Conventional or SW switching process in which the direction of the applied magnetic field is opposite to the direction of the easy axis.

Conventional or SW Switching

- Pulsed magnetic field is applied anti-parallel to the initial magnetization.
- Magnetization then undergoes multiple rotations around the local effective field to reach the final equilibrium direction.
- Switching is a relaxation process towards the stable equilibrium, and hence the damping process is crucial.

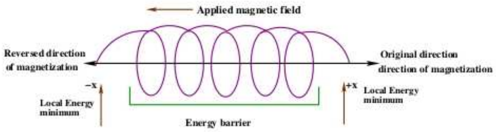

Figure : Switching of magnetization by coherent rotation.

[E.C. Stoner & E.P. Wohlfarth, *Phil. Trans. R. Soc. A* **240**, 599 (1948)].

Precessional Switching

Types

1. Field induced precessional switching in nanofilms.
2. Current induced precessional switching in nanopillars.

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Field Induced Precessional Switching

Pulsed magnetic field is applied normal to the direction of the initial magnetization and the change in orientation of magnetization is obtained by undergoing wide angle precession under the influence of applied magnetic field.

Field Induced Precessional Switching

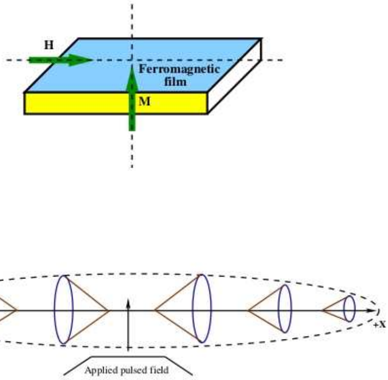


Figure : Switching of magnetization by wide angle precession.

[C.H. Back et al, *Phys. Rev. Lett.* **81**, 3251 (1998).]

Current Induced Precessional Switching

- Theory: J. C. Slonczewski, *J. Magn. Magn. Mater.* **159**, L1 (1996). & L. Berger, *Phys. Rev. B* **54**, 9353 (1996).
- Experiment: E. B. Myers, D. C. Ralph, J. A. Katine, R. N. Louie, and R. A. Buhrman, Science **285**, 867 (1999).

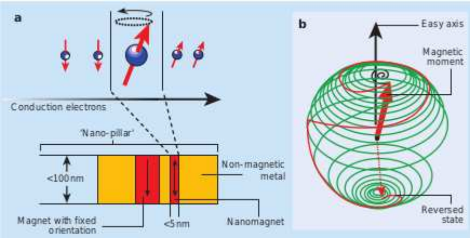
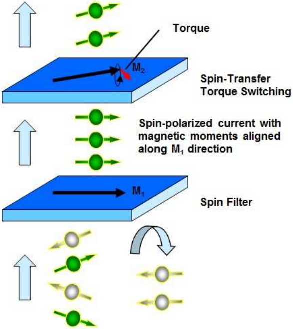


Figure : A schematic representation of current induced precessional switching.



Some other ways

- Current induced precessional switching in trilayer nanopillar has been widely studied both theoretically, and experimentally as well as through numerical and micromagnetic simulations.
- Effect of various anisotropies like shape anisotropy, magneto-crystalline anisotropy and surface anisotropy is studied.
- Irradiation with a laser pulse quenches the magnetization by laser induced heating above the Curie temperature.
- Laser pulses modify the magnetic anisotropy, thus inducing the reorientation and / or precession of spins.
- By applying a small radio frequency field pulse.
- By adding spacer and fixed magnetic layer above the trilayer.

Impact of biquadratic coupling on magnetization switching

Motivation

- Growing multilayer nanopillars in an ideal layer by layer fashion 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.
- Impact of biquadratic coupling on current induced magnetization switching in the Co/Cu/Ni-Fe nanopillar device.

Co/Cu/Ni-Fe nanopillar with Biquadratic coupling: Model

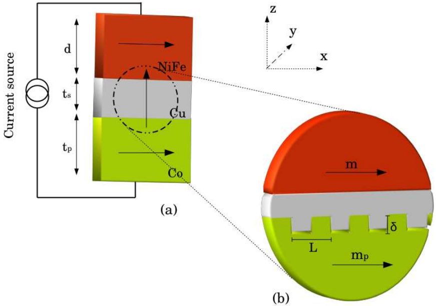


Figure : (a). Geometry of the Co/Cu/Ni-Fe nanopillar device. (b). In the zoomed view, we can see the pinned layer (Co) have periodic interfacial terraces with a period L and a height δ.

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,

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

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

Where,

- $\tau = \gamma M_s t$
- $a_j = \frac{pJ\hbar}{\mu_0 e d M_s^2}$
- $\mathbf{h}_{eff} = \mathbf{h}_{ma} + \mathbf{h}_{shape} + \mathbf{h}_{ext} + \mathbf{h}_{bqc}$

Effective field acting on the free layer

$$\mathbf{h}_{ma} = h_a m^x \mathbf{e}^x \tag{2}$$
$$\mathbf{h}_{shape} = -(N_x m^x \mathbf{e}^x + N_y m^y \mathbf{e}^y + N_z m^z \mathbf{e}^z) \tag{3}$$
$$\mathbf{h}_{ext} = h_e \mathbf{e}^y \tag{4}$$
$$\mathbf{h}_{bqc} = h_b m^x \mathbf{e}^x \tag{5}$$
$$\mathbf{h}_{eff} = (h_a + h_b) m^x \mathbf{e}^x + h_e \mathbf{e}^y - N_z m^z \mathbf{e}^z. \tag{6}$$

Where,

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

Critical current density for magnetization switching

LLGS equation(Eq. 1) in the component form for the static case as,

$$(h_e + N_z m^y)m^z - a_j({m^y}^2 + {m^z}^2) = 0, \tag{7}$$

$$-(h_a + h_b + N_z)m^x m^z + a_j m^x m^y = 0, \tag{8}$$

$$(h_a + h_b)m^x m^y - h_e m^x + a_j m^x m^z = 0. \tag{9}$$

Solving Eqs. (7 - 9) algebraically, the time independent solution for m^x, m^y & m^z are obtained as

$$m^y = \frac{h_e(h_a + h_b + N_z)}{a_j^2 + (h_a + h_b)(h_a + h_b + N_z)} \cdot \tag{10}$$

$$m^z = \frac{h_e a_j}{a_j^2 + (h_a + h_b)(h_a + h_b + N_z)} \cdot \tag{11}$$

$$m^x = \left[1 - \frac{h_e^2[a_j^2 + (h_a + h_b + N_z)^2]}{[a_j^2 + (h_a + h_b)(h_a + h_b + N_z)]^2}\right]^{\frac{1}{2}} \cdot \tag{12}$$

Critical current density for magnetization switching Contd.

- 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,

$$h_e^2[a_j^2 + (h_a + h_b + N_z)^2] = [a_j^2 + (h_a + h_b)(h_a + h_b + N_z)]^2. \quad (13)$$

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

$$a_j^2 = -(h_a + h_b)(h_a + h_b + N_z). \quad (14)$$

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

$$J_c = \left(\frac{\mu_0 e d M_s^2}{p\hbar}\right)\left[(h_a + h_b)(h_a + h_b + N_z)\right]^{\frac{1}{2}}. \quad (15)$$

Values of Various Parameters and Critical Current Density

Parameters	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	$0.795 \times 10^6 Am^{-1}$
Exchange stiffness constant of Ni-Fe	A_{ex}	$2.1 \times 10^{-11} Jm^{-1}$
Thickness of the free layer (Ni-Fe)	d	$4 \times 10^{-9} m$
Thickness of the spacer layer (Cu)	t_s	$2 \times 10^{-9} m$
Height of the roughness of Co layer	δ	$0.8 \times 10^{-9} m$
Period of the roughness of Co layer	λ	$40 \times 10^{-9} m$

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The critical current density in the presence of the biquadratic coupling is $1.0914 \times 10^{12} Am^{-2}$.

Impact of biquadratic coupling on switching time

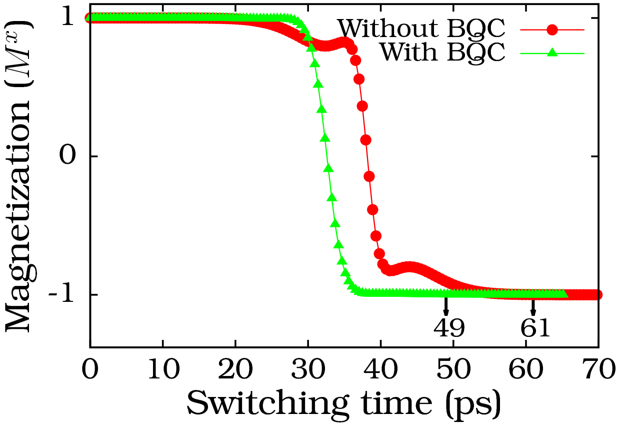

Figure : A plot of free layer magnetization versus switching time for the Co/Cu/Ni-Fe nanopillar in the presence and absence of the biquadratic coupling for an applied current density of $J = 5 \times 10^{12} Am^{-2}$.

Impact of roughness on switching time

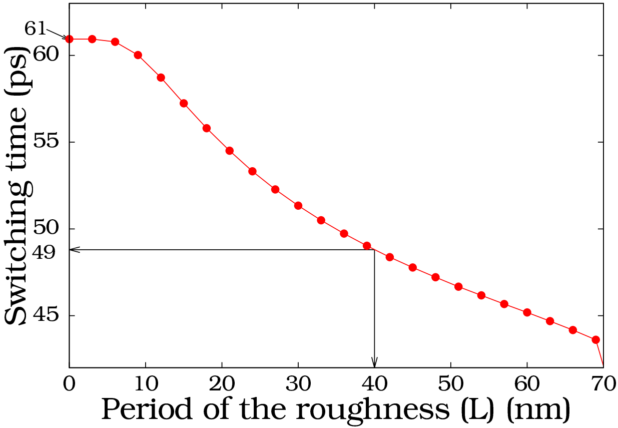

Figure : A plot of the period of the roughness versus switching time for an applied current density of $J = 5 \times 10^{12} Am^{-2}$.

Conclusion

Summary

1. Current induced precessional magnetization switching in Co/Cu/Ni-Fe nanopillar was studied in the absence and in the presence of Biquadratic Coupling.
2. Value of the critical current density required to initiate the magnetization switching is calculated.
3. The Switching time is calculated in the presence and in the absence of the biquadratic coupling.
4. Switching time reduces when there exists the biquadratic coupling between the ferromagnetic layers.

References

- J. C. Slonczewski, *J. Magn. Magn. Mater.*, **159**, L1, (1996).
- C. Chappert et al, *Nat. Mater.*, **6**, 813, (2007).
- M. Stiles, in *Ultrathin Magnetic Structures III*, edited by J. Bland and B. Heinrich (Springer Berlin Heidelberg, 2005), pp. 99-142.
- S. Demokritov et al, *Phys. Rev. B*, **49**, 720 (1994).
- D. Aravinthan et al, *AIP Advances*, **5**, 077166 (2015).
- M. Daniel et al, *J. Magn. Magn. Mater.*, **322**, 675 (2010).
- J. Zhang et al, *IEEE Trans. Magn.*, **32**, 4630 (1996).

"The magnet´s mystery, explain that to me!
No greater mystery but love and hate".

-Johann Wolfgang von Goethe (1749 - 1832).

Thank You.