Influence of Orange Peel Coupling on Magnetization Switching in Nanopillar

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Outline of Talk

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Introduction

Magnetization Switching

Switching of the state of magnetization from one stable configuration to another desired stable configuration.

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Methods

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

Conventional or Stoner-Wohlfarth (SW) Switching

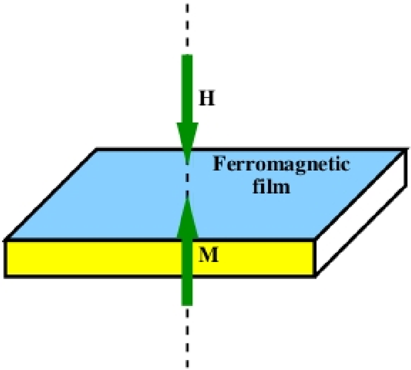

Figure: Conventional or SW switching process in which the direction of the applied magnetic field is opposite to the direction of the easy axis.

Conventional or SW Switching

- Magnetic field is applied antiparallel to the direction of initial magnetization and the change of direction of magnetization is achieved by undergoing multiple rotations around the effective field.
- Switching is a relaxation process towards the stable equilibrium, and hence the damping process is crucial.

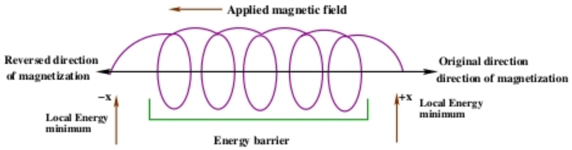

Figure: Switching of magnetization by coherent rotation.

Precessional Switching

Types

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

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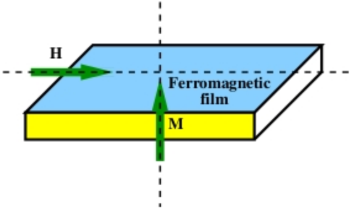
Field Induced Precessional Switching

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



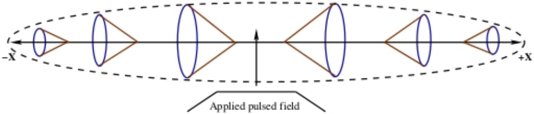


Figure: Switching of magnetization by wide angle precession.

Current Induced Precessional Switching

- Current passes through the nanopillar, the average spin of the electrons is aligned along the magnetization vector.
- The angular momentum of the electrons rotate when the electrons go from one layer to another.
- The source of this rotation is the spin transfer torque which precess the free layer magnetization.

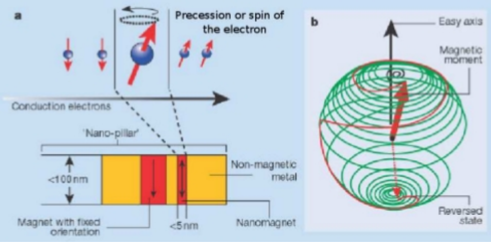


Figure: A schematic representation of current induced precessional switching.

Importance of Switching Time

Switching Time

The time taken to switch the magnetization from one stable configuration to another desired stable configuration.

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Importance

- 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.

Geometry of the ferromagnetic Nanopillar

- The ferromagnetic nanopillar device consists of two ferromagnetic layers (FM1, FM2) separated by a nonmagnetic metal (NM) called the spacer.
- The free layer is assumed to be single magnetic domain of 3 nm thickness with the lateral dimension 30 x 60 nm^2 .

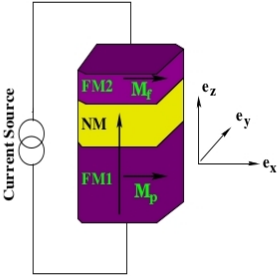

Figure: A sketch representing the geometry of a nanopillar with the current source.

Magnetization Dynamics

The free layer magnetization dynamics of the nanopillar device is governed by the LLGS equation and can be written as

$$\frac{d\mathbf{M}}{dt} = -\gamma\left[\mathbf{M}\times\mathbf{H}_{eff}\right] + \alpha\left[\mathbf{M}\times\left(\mathbf{M}\times\mathbf{H}_{eff}\right)\right] + \gamma a_j\left[\mathbf{M}\times\left(\mathbf{M}\times\mathbf{M}_p\right)\right]. \quad (1)$$

$$\text{Effective field}: \quad \mathbf{H}_{eff} = \mathbf{H}_{shape} + \mathbf{H}_{ani} + \mathbf{H}_{sur} + \mathbf{H}_{ext}. \quad (2)$$

$$\text{Shape anisotropy}: \quad \mathbf{H}_{shape} = D_x M_f^x + D_y M_f^y + D_z M_f^z, \quad (3)$$

where $D_x = -4\pi N_x$, $D_y = -4\pi N_y$, and $D_z = -4\pi N_z$.

The free layer is assumed to be parallel to the xy-plane and hence $N_x = N_y = 0$ and $N_z = 1$.

Magnetization Dynamics contd.

$$\text{Magnetocrystalline anisotropy}: \mathbf{H}_{ani} = H_a M_f^x \mathbf{e}_x, \ H_a = \frac{2K_u}{M_s} \quad (4)$$

$$\text{External field}: \quad \mathbf{H}_{ext} = H_e \mathbf{e}_y \quad (5)$$

$$\text{Surface anisotropy}: \quad \mathbf{H}_{sur} = H_i M_f^z \mathbf{e}^z, \quad H_i = \frac{2I_u}{M_s d}. \quad (6)$$

The component form of the LLGS equation when $\alpha = 0$ is

$$\frac{dM^x}{dt} = (D_z + H_i - D_y) M^z M^y - H_e M^z + a_j (M^{y2} + M^{z2}) \quad (7)$$

$$\frac{dM^y}{dt} = (H_i - H_a + D_z - D_x) M^x M^z + a_j M^x M^y \quad (8)$$

$$\frac{dM^z}{dt} = (D_y - D_x - H_a) M^x M^y + H_e M^x - a_j M^x M^z \quad (9)$$

Threshold current density

The time independent solution of LLGS equation is

$$M^x = \left[1 - \frac{[(D_x - D_z - H_i + H_a)^2 + a_j^2]H_e^2}{[(D_y - D_x - H_a)(D_z - D_x + H_i - H_a) + a_j^2]^2}\right]^{\frac{1}{2}} \quad (10)$$

$$M^y = \frac{(D_x - D_z - H_i + H_a)H_e}{[(D_y - D_x - H_a)(D_z - D_x + H_i - H_a) + a_j^2]} \quad (11)$$

$$M^z = \frac{H_e a_j}{[(D_y - D_x - H_a)(D_z - D_x + H_i - H_a) + a_j^2]} \quad (12)$$

Initial Condition : $M^x = 1$, $M^y = 0$, and $M^z = 0$.
Threshold current density is

$$J_c = \left(\frac{\gamma e d M_s}{\hbar p}\right)[H_a(H_i - H_a - 4\pi)]^{\frac{1}{2}} \quad (13)$$

Magnetization Switching curve

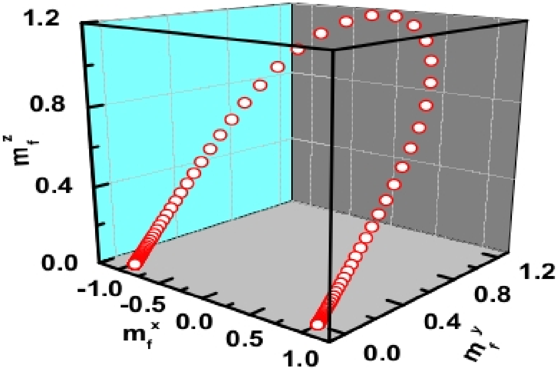

Figure: The magnetization trajectory for spin-transfer induced precessional reversal in the $(m^x\ ,\ m^y\ ,\ m^z)$ space.

Magnetization Vs Switching time

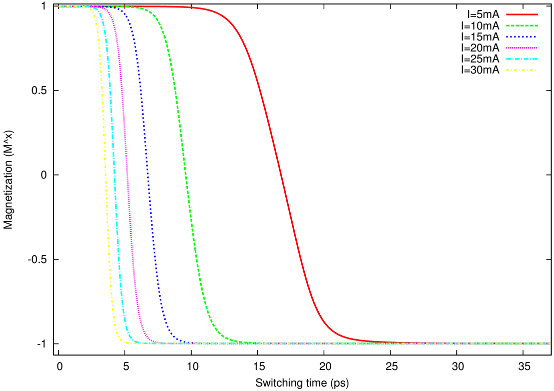

Figure: Current induced switching curves as a plot of magnetization Vs switching time for different currents.

Orange Peel Coupling

- In 1962, Neel pointed out that there should be ferromagnetic coupling between adjacent films due to magnetic dipoles at the interface induced by a morphological corrugation.
- The left panel shows the fringing field outside a rough surface of a material with a uniform magnetization.
- The middle panel shows how the fringing fields change in the presence of another interface with correlated roughness for the case of parallel magnetizations.

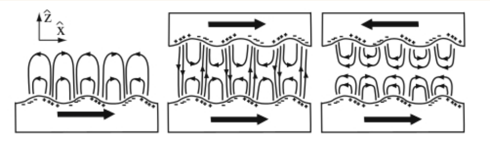

Figure: Orange peel coupling from correlated roughness.

Orange Peel Coupling Contd.

The field corresponding to Neel coupling between two ferromagnetic layers (free and pinned), separated by a nonmagnetic spacer (thickness d) with a correlated interface waviness with amplitude h and wavelength λ is given as

$$\mathbf{H}_N = \frac{\pi^2 h^2 \mathbf{M}}{\sqrt{2}\lambda M_s d} exp\left(-\frac{2\sqrt{2}\pi t_s}{\lambda}\right). \qquad (14)$$

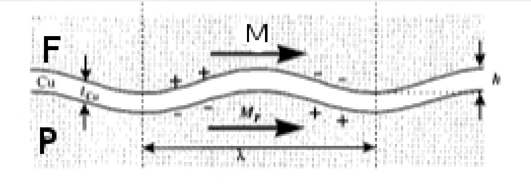

Figure: Orange peel coupling from correlated roughness.

Effective field

The effective field in the free layer becomes,

$$\mathbf{H}_{eff} = \mathbf{H}_{shape} + \mathbf{H}_{ani} + \mathbf{H}_{sur} + \mathbf{H}_N + \mathbf{H}_{ext}. \quad (15)$$

$$\text{Neel field :} \quad \mathbf{H}_N = K_n M_f^z \mathbf{e}^z, \quad (16)$$

$$\text{where} \quad K_n = \frac{\pi^2 h^2}{\sqrt{2}\lambda M_s d} exp\left(-\frac{2\sqrt{2}\pi t_s}{\lambda}\right). \quad (17)$$

Threshold current density

The time independent solution of LLGS equation is

$$M^x = \left[1 - \frac{[(D_x - D_z - H_i - K_n + H_a)^2 + a_j^2]H_e^2}{[(D_y - D_x - H_a)(D_z - D_x + H_i + K_n - H_a) + a_j^2]^2}\right]^{\frac{1}{2}} \quad (18)$$

$$M^y = \frac{(D_x - D_z - H_i - K_n + H_a)H_e}{[(D_y - D_x - H_a)(D_z - D_x + H_i + K_n - H_a) + a_j^2]} \quad (19)$$

$$M^z = \frac{H_e a_j}{[(D_y - D_x - H_a)(D_z - D_x + H_i + K_n - H_a) + a_j^2]} \quad (20)$$

Initial Condition : $M^x = 1$, $M^y = 0$, and $M^z = 0$.
Threshold current density is

$$J_c = \left(\frac{\gamma e d M_s}{\hbar p}\right)[H_a(H_i + K_n - H_a - 4\pi)]^{\frac{1}{2}} \quad (21)$$

Magnetization Vs Switching time

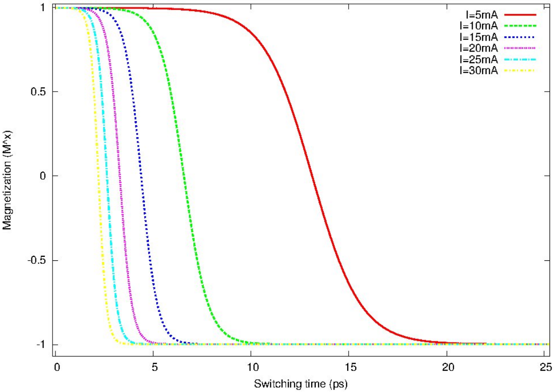

Figure: Current induced switching curves as a plot of magnetization Vs switching time for different currents .

Magnetization Switching time variation

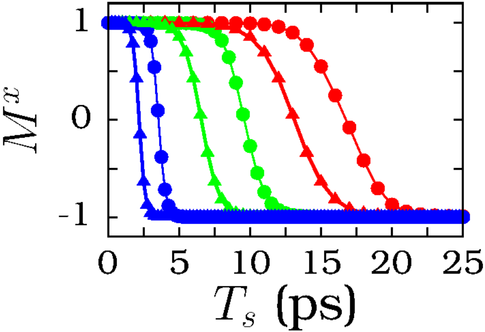

Figure: Switching time variation in the absence and presence of Orange Peel Coupling. Ts due to inthe absence of Orange Peel Coupling represented by Filled circles. Ts due to in the presence of Orange Peel Coupling represented by Filled triangles. Red: I=5mA, Green: I=10mA, Blue: I=30mA.

Switching time for Various thickness of the free layer

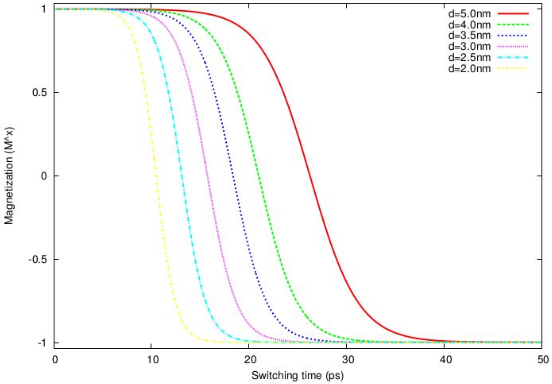

Figure: Current induced switching curves as a plot of magnetization vs switching time for different thickness of the free layer.

Conclusion

1. Current induced precessional switching of Magnetization in a Co/Cu/Co nanopillar was studied in the absence and presence of Orange Peel Coupling.
2. The Switching time reduces when the strength of current is increased.
3. The Switching time reduces when the thickness of the free layer is decreased.
4. The Orange Peel Coupling influences the switching time significantly.

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Thank you