Spin Transfer Torque Switching in Pentalayer Nanopillar

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2. Types of Switching

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Introduction

What is Magnetization Switching?

Direction of magnetization is switched from one stable configuration to another desired stable configuration.

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Applications

- Ultra-high density magnetic data storages.
- Magnetic Random Access Memories (MRAM).
- Spintronic devices.
- High frequency microwave oscillators.

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.

Types of Switching

Methods

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

Conventional or Stoner-Wohlfarth (SW) Switching

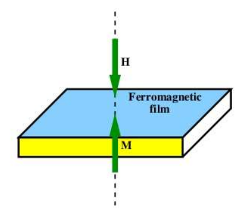

Figure : Conventional or SW switching process in which the direction of the applied magnetic field is opposite to the direction of the easy axis.

Conventional or SW Switching

- Apply a magnetic field pulse antiparallel 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.

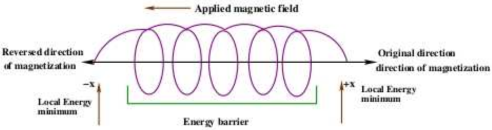

Figure : Switching of magnetization by coherent rotation.

[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.

Precessional Switching

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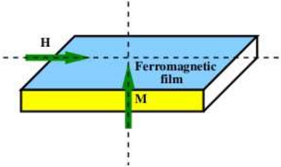
1. Field induced precessional switching in nanofilms.
2. Current induced precessional switching in nanopillars.

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



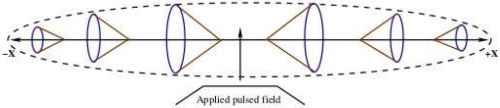


Figure : Switching of magnetization by wide angle precession.

[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).

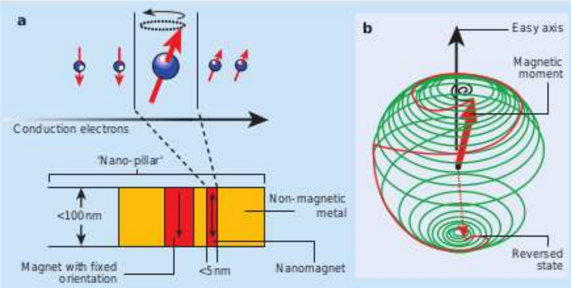


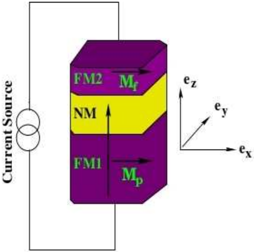
Figure : A schematic representation of current induced precessional switching.

Current Induced Precessional Switching

- Current passes through the fixed layer, the spin of the electrons are aligned along the magnetization vector.
- When polarized electrons flow from one layer to another, the angular momentum of each electron rotates.
- These electrons develop a torque with the magnetization of the free layer.
- This torque forces the free layer magnetization to rotate out of the film plane.
- This produces a demagnetization field orthogonal to the film plane about which the magnetization precesses.
- When the free layer magnetization reaches the desired state, the current is switched off precisely.

Curret Induced Precessional Switching in trilayer

- Current induced precessional switching in trilayer nanopillar has been widely studied both theoretically, and experimentally as well as through numerical and micromagnetic simulations.
- Applied current density: $10^{12} A/m^2$
- Switching time : pico seconds.
- For memory applications, the switching time is in nanosecond regime with small current density.



Some other methods

- Using various anisotropies like shape anisotropy, magnetocrystalline anisotropy and surface anisotropy.
- 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.

Our Model

Geometry of Pentalayer Nanopillar

- The Pentalayer nanopillar device consists of three ferromagnetic layers (Pinned1, Pinned2, Free) and two nonmagnetic metal layers (NM) called the spacer.

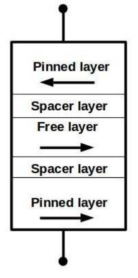


Figure : A sketch representing the geometry of a Pentalayer Nanopillar.

Our Model

The role of the top pinned layer

- The role of the top pinned layer is to provide an additional source of spin-polarized electrons to the free layer.
- When the two pinned layers are aligned, the spin-polarized electrons from the two pinned layers exert torque in opposite directions, resulting in a much smaller net torque.
- When the two pinned layers are antialigned with respect to one another, the spin currents from both fixed layers exert torque in the same direction, resulting in a much larger net torque.

[G. D. Fuchs et al, *Appl. Phys. Lett.*, **86**, 152509, (2005).]

Magnetization Switching Dynamics

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

$$\frac{d\mathbf{m}}{d\tau} = -[\mathbf{m} \times \mathbf{h}_{\mathbf{eff}}] - \alpha[\mathbf{m} \times (\mathbf{m} \times \mathbf{h}_{\mathbf{eff}})] + a_j[\mathbf{m} \times [(\mathbf{m} \times \mathbf{m}_{p1})]] + a_j[\mathbf{m} \times [(\mathbf{m} \times \mathbf{m}_{p2})]]. \quad (1a)$$

$$\mathbf{m} = (m^x, m^y, m^z), \qquad \mathbf{m}^2 = m^{x2} + m^{y2} + m^{z2} = 1. \quad (1b)$$

- $\tau = \gamma M_s t$
- $a_j = \frac{pJ\hbar}{\mu_0 edM_s^2}$
- $\mathbf{m_{p1}} = \cos\theta_1 \mathbf{e}^x + \sin\theta_1 \mathbf{e}^y$
- $\mathbf{m_{p2}} = \cos(\pi + \theta_2)\mathbf{e}^x + \sin(\pi + \theta_2)\mathbf{e}^y$

Magnetization Switching Dynamics contd.

Effective Magntic Field

$$\text{Effective field : } \quad \mathbf{h}_{eff} = \mathbf{h}_{shape} + \mathbf{h}_{ani} + \mathbf{h}_{ext}. \tag{2}$$

$$\text{Shape anisotropy : } \mathbf{h}_{shape} = -(N_x m^x \mathbf{e}^x + N_y m^y \mathbf{e}^y + N_z m^z \mathbf{e}^z), \tag{3}$$

The free layer lies in the xy-plane and hence $N_x = N_y = 0$ and $N_z = 1$.

$$\text{Magnetocrystalline anisotropy : } \mathbf{h}_{ani} = h_a m^x \mathbf{e}^x \tag{4}$$

$$\text{External field : } \quad \mathbf{h}_{ext} = h_e \mathbf{e}^y. \tag{5}$$

$$\mathbf{h}_{eff} = h_a m^x \mathbf{e}^x + h_e \mathbf{e}^y - N_z m^z \mathbf{e}^z. \tag{6}$$

The component form of LLGS equation

The component form of the LLGS equation is

$$\frac{dm^x}{d\tau} = (h_e + N_z m^y)m^z - \alpha\left[(h_e - h_a m^y)m^x m^y - (h_a + N_z)m^x m^{z2}\right] + a_j[m^x m^y(\sin\theta_1 + \sin\theta_2) - (m^{y2} + m^{z2})(\cos\theta_{1+} \cos\theta_2)] \tag{7}$$

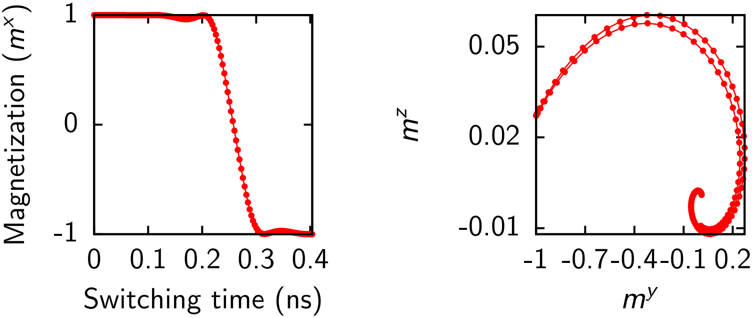
$$\frac{dm^y}{d\tau} = -(h_a + N_z)m^x m^z + \alpha\left[(h_e - h_a m^y)m^{x2} + (h_e + N_z m^y)m^{z2}\right] - a_j[(m^{x2} + m^{z2})(\sin\theta_1 + \sin\theta_2) - m^x m^y(\cos\theta_{1+} \cos\theta_2)] \tag{8}$$

$$\frac{dm^z}{d\tau} = (h_a m^y - h_e)m^x - \alpha\left[(h_a + N_z)m^{x2} m^z + (h_e + N_z m^y)m^y m^z\right] - a_j[m^y m^z(\sin\theta_1 + \sin\theta_2) + m^x m^z(\cos\theta_1 + \cos\theta_2)] \tag{9}$$

Numerical Parameters

Parameters / Constants	Symbol	Value
Charge of electron	e	$1.602 \times 10^{-19} C$
Reduced Planck's Constant	$\hbar$	$1.0551 \times 10^{-34} Js$
Gyromagnetic ratio of free e^-	γ	$2.21 \times 10^5 mA^{-1}s^{-1}$
Permeability of free space	μ_0	$1.257 \times 10^{-6} JA^{-2}m^{-1}$
Polarization factor	p	0.3
Gilbert damping parameter	α	0.003
Magnetocrystalline anisotropy of NiFe	h_a	0.01
Saturation magnetization of NiFe	M_s	$0.795 \times 10^6 Am^{-1}$
Thickness of the free layer	d	$2.8 \times 10^{-9} m$
Applied current density	J	$3.0 \times 10^{11} Am^{-2}$
Applied magnetic field	h_e/h_a	0.4

Magnetization Vs Switching time



(a) Switching time

(b) Magnetization trajectory

Figure : Double pinned layer in standard configuration.

Switching Time = 0.296 ns

Magnetization Switching curve

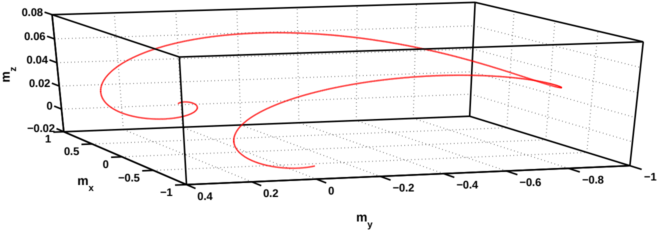


Figure : The magnetization trajectory for spin-transfer induced precessional reversal in the $(m^x\ ,\ m^y\ ,\ m^z)$ space.

First Pinned Layer Biasing Configuration (FPLBC)

- First Pinned layer is biased to 24°. i.e. $\theta_1 = 24^\circ,\ \theta_2 = 0^\circ$.
- $\mathbf{m_{p1}} = \cos\theta_1 \mathbf{e}^x + \sin\theta_1 \mathbf{e}^y = 0.9\mathbf{e}^x + 0.4\mathbf{e}^y$
- $\mathbf{m_{p2}} = \cos(\pi + \theta_2)\mathbf{e}^x + \sin(\pi + \theta_2)\mathbf{e}^y = -\mathbf{e}^x$

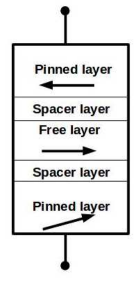


Figure : A sketch representing the geometry of a FPLBC.

First Pinned Layer Biasing Configuration (FPLBC)

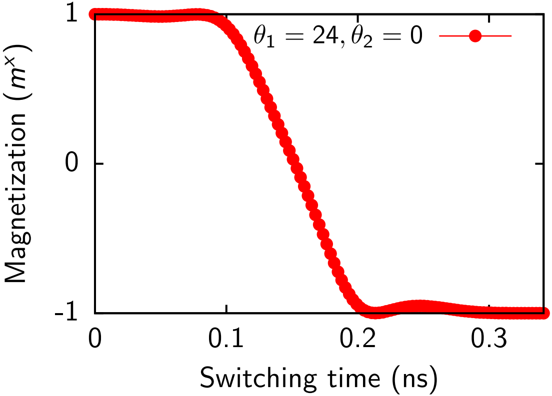


Figure : Magnetization Vs Switching time.

Switching Time = 0.195 ns

First Pinned Layer Biasing Configuration (FPLBC)

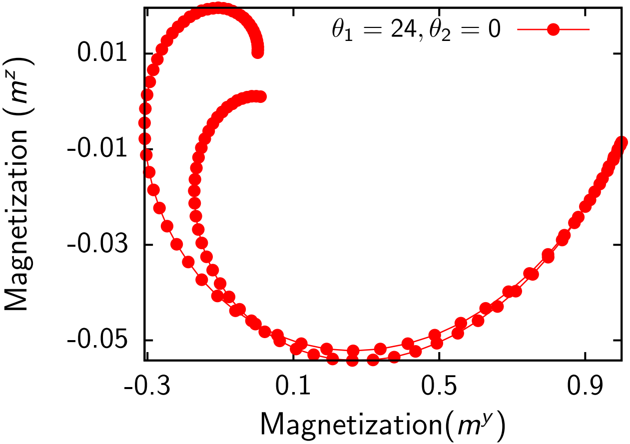


Figure : The magnetization trajectory.

Double Pinned Layer Biasing Configuration (DPLBC)

- Both Pinned layers are biased to 24°. i.e. $\theta_1 = 24^\circ$, $\theta_2 = 24^\circ$.
- $\mathbf{m_{p1}} = \cos\theta_1 \mathbf{e}^x + \sin\theta_1 \mathbf{e}^y = 0.9\mathbf{e}^x + 0.4\mathbf{e}^y$
- $\mathbf{m_{p2}} = \cos(\pi + \theta_2)\mathbf{e}^x + \sin(\pi + \theta_2)\mathbf{e}^y = -0.9\mathbf{e}^x - 0.4\mathbf{e}^y$

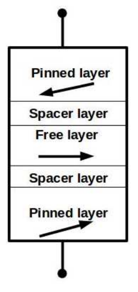


Figure : A sketch representing the geometry of a DPLBC.

Double Pinned Layer Biasing Configuration (DPLBC)

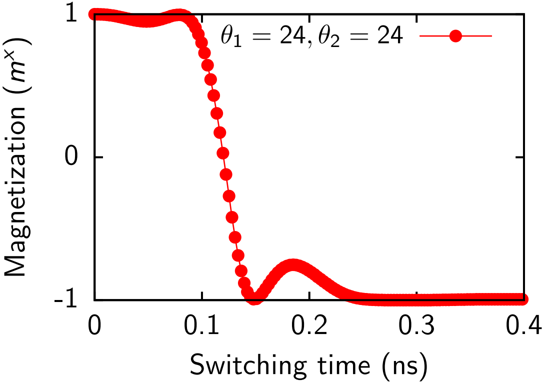


Figure : Magnetization Vs Switching time.

Switching Time = 0.140 ns

Double Pinned Layer Biasing Configuration (DPLBC)

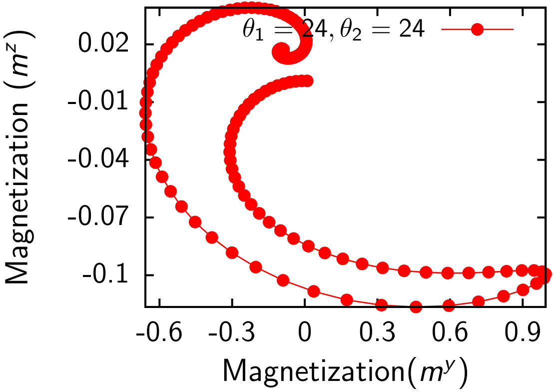


Figure : The magnetization trajectory.

Free Layer Biasing Configuration (FLBC)

- Free layer is biased by applying external field.
- $h_e/h_a = 0.4$

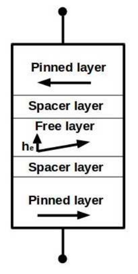


Figure : A sketch representing the geometry of a FLBC.

Free Layer Biasing Configuration (FLBC)

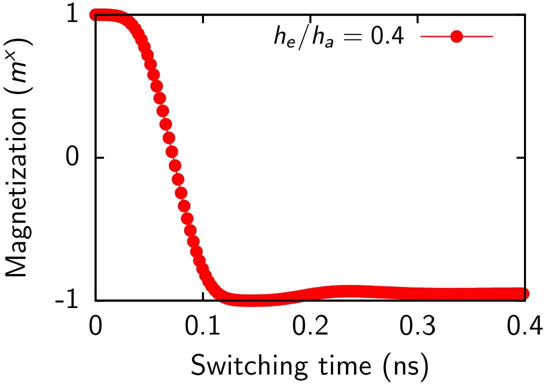


Figure : Magnetization Vs Switching time.

Switching Time = 0.108 ns

Free Layer Biasing Configuration (FLBC)

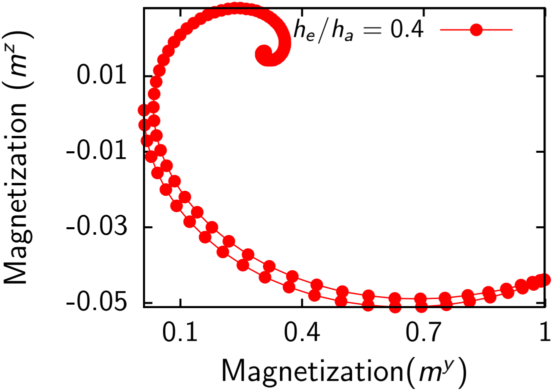


Figure : The magnetization trajectory.

Conclusion

1. Current induced precessional magnetization switching in a pentalayer nanopillar was studied for different biasing configurations.
2. The switching time reduces when the layers are biased.
3. The lowest switching time is obtained for free layer biasing configuration.

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Magnetic Atoms, such as Iron, keep
Unpaired Electrons in their middle shell,
Each one a spinning Magnet that would leap
The Bloch Walls where at antiparallel
Domains converge. Diffuse Material
Becomes Magnetic when another Field
Aligns domains like Seaweed in a swell
How nicely microscopic forces yield,
In Units growing invisible, the World we wield!

John Updike, from "The Dance of the Solids", Midpoint and Other Poems, 1969 .

Thank You.