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Effect Of Magnetic Anisotropies On The Magnetization Switching In Composite Free Layer Spin Valves

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Abstract: Magnetization dynamics of composite free layer spin valve is investigated. The spin dynamics is modelled by Landau-Lifshitz-Gilbert-Slonczewski equation. Influence of magneto crystalline anisotropy and interface uniaxial anisotropy in the presence of Spin Transfer Torque (STT) is studied using fourth order Runge-Kutta method. Switching time and critical current density is calculated. Trajectories of spin components are plotted and effect of STT with respect to polarisation and thickness of the free layer on magnetization dynamics is studied. Switching is found to be faster and current density is also decreased in anisotropic material.

Key words: composite magnetic multilayer, spin valve pillars, LLGS equation, Runge-Kutta method, magnetization switching.

1. INTRODUCTION:

The research in magnetic multilayer systems has rapidly advanced in the past decade and novel magnetic devices of atomic dimensions are engineered. These systems operate in quiet a different way and their magnetization dynamics is driven by dipolar interaction, exchange interaction and anisotropic interactions [1, 2]. Generally the dynamics of these systems are modelled by Nonlinear Evolution equation which depends on spin degrees of freedom of electrons. The development of spin based electronics leads to the fast manipulation of electron spin in lower dimensions. Study of spin transport through magnetic multilayer in the form of thin films has contributed much to the field of spintronics. In this line, spin valve and magnetic tunnel junction (MTJ) are the typical multilayer devices which use the spin transfer torque (STT). This effect was predicted by Lue Berger and John Slonczewski in 1996 [3, 4] and the dynamics of magnetization in these systems is modelled by Landau-Liftshitz-Gilbert-Slonczewski (LLGS).

The basic element of an STT-Magnetic Random Access Memory (MRAM) is a magnetic tunnel junction (MTJ), a sandwich of two magnetic layers separated by a thin nonmagnetic spacer. Here the magnetization of the pinned layer is fixed and the magnetization direction of the free layer can be switched between the two states parallel and anti-parallel to the fixed magnetization direction. Switching in STT-MRAM occurs due to the spin-polarized current flowing through the MTJ. Different structures of MTJ are available; three layer with in-plane magnetization of the free layer (in plane MTJs) [5], in-plane penta-layer MTJs [6], three-layer MTJs with perpendicular magnetization (pMTJs) [7]. Direct measurement of both magnitude and direction of spin transfer torque in MTJ is reported by Robert A. Buhrman et.al. [8].

Therefore, research in new materials and structures of MTJ is gaining momentum. When compared with a monolithic free layer, a five layered MTJ with a composite free layer shows reduction in magnetization switching time [9] and decrease in current density [10]. Spin transfer torque induced collective excitations for CFAS spin valve pillar has been studied widely [11].

There are two immediate advantages in using exchange-coupled composite media first, the writing capability of the media could be dramatically improved without losing its thermal stability, secondly, the remanent coercivity of the media is much less sensitive to the angle dispersion compared to a perpendicular media [12]. Moreover, composite layers are also used as free layers because of their high thermal stability. For a reliable memory cell, which has to keep the stored information longer than ten years, higher thermal stability is required.

When this composite layer based devices are put into service, they are subjected to electric and magnetic fields. The spin magnetic moments respond to this and the study of their dynamics is very much required to engineer devices with better efficiency. With this motivation, we investigate the magnetization dynamics and switching behaviour in the composite layer spin valve pillar which has all the above said qualities. This paper is organized as follows. In section II, the physical model of the composite free layer is discussed and the LLGS equation which represents the spin dynamics is framed. In section III, the extended LLGS equation is solved using Runge-Kutta method. In section IV, the solutions are plotted to get a better qualitative behaviour. The results are concluded in section V.

PHYSICAL MODEL:

A composite refers to two or more reinforced layer. A conventional spin valve pillar consists of a non magnetic layer sandwiched between two ferromagnetic layers, one a thicker layer whose magnetization is fixed and other a thin layer which has free magnetization. Traditionally the free layer is a monolithic layer, but if the free layer is replaced by two or more layers of different magnetic materials, then it is called as composite free layer(CFL) or synthetic free layer(SyFL). The inter layer exchange coupling which can be changed by spacer's thickness [13,14] is due to Ruderman, Kittel, Kasuya and Yoshida (RKKY) interaction. When the magnetic layers are different, the structures have an uncompensated magnetic moment hence the interlayer exchange coupling is positive, then it is referred as synthetic ferrimagnet. When the magnetic layers are identical, the structures have zero magnetic moment and the interlayer exchange coupling is negative, and it is called as synthetic antiferromagnet (SyAF) [15-16]. The nonmagnetic ruthenium is used as spacer between the two free layers. The antiferromagnetic coupling through RKKY interaction is achieved by altering the thickness of ruthenium layer.

MODELING THE INTERACTIONS IN THE COMPOSITE FREE LAYER SPIN VALVE:

The Extended Llgs Equation:

Spin valve pillar with composite free layer has a pinned layer whose magnetization vector $\overrightarrow{S_0}$ is in the direction of external magnetic field. Spin polarised current is generated when electrons pass through this pinned layer. $\vec{S}_1$ and $\vec{S}_2$ are spin vectors of two free layers. The spin polarized electrons drift through the spacer and when it enters the free layer it tries to align in the direction of $\vec{S}_1$. There it encounters a torque due to strong coupling between

$\vec{S}_1$ and $\vec{S}_2$. Spin transfer torque influences the layer F_1, which is induced both by the polarizer F_0 and STT due to the layer F_2. This torque has both longitudinal and transverse components and called as Slonczewski's Spin Transfer Torque. The STT components can be written as [13],

$$\tau_{\parallel 1} = I\left[\vec{S}_1 \times \vec{S}_1 \times (a_1\vec{S}_1 + a_1\vec{S}_2)\right]$$
$$\tau_{\perp 1} = I\ \left[\vec{S}_1 \times (b_1\vec{S}_1 + b_1\vec{S}_2)\right]$$
$$\tau_{\parallel 2} = I\left[\, a\vec{S}_2 \times (\vec{S}_2 \times \vec{S}_1)\right]$$
$$\tau_{\perp 2} = I\ b\left[\vec{S}_2 \times \vec{S}_1\right]$$

We study the evolution of magnetization of the system using the extended LLGS equation. In the semi classical limit, the LLGS equation [13, 17, 18] for the two free layers can be written as,

$$\frac{d\vec{S}_i}{dt} + \alpha\vec{S}_i \times \frac{d\vec{S}_i}{dt} = \Gamma_i \qquad (1)$$

and $\Gamma_i = -\gamma_g\mu_0\vec{S}_i \times \vec{H}_{effe} + \gamma_g\, b_j\tau_i$

when, $b_j = \frac{\hbar PJ}{ed_i m_s}$

for i=1,2 , here $\vec{S}_i$ is the unit vector, $\overrightarrow{H}_{effe}$ is the effective field which comprises both external and internal fields, $\tau_i = \tau_{\parallel i} + \tau_{\perp i}$ is the current induced torque acting on $\vec{S}_i$, α is the Gilbert damping parameter, b_j is coefficient of spin torque, m_s is the saturation magnetization value for both magnetic layers of CFL, d_i is the thickness of the free layers 1 and 2 respectively, J is current density and P is the polarisation factor. The effective field includes,

$H_{eff} = H_{shape} + H_{ani} + H_{int} + H_{ext}$

Where,

$H_{shape} = D_x S^x e_x + D_y S^y e_y + D_z S^z e_z$

$S^x = -4\pi N_x$, $S^y = -4\pi N_y$ and $S^z = -4\pi N_z$

N_x , N_y, N_z are demagnetization factors and e_x , e_y and e_z are unit vectors along x, y and z directions respectively.

$H_{ani} = A_c S^x e_x$

$A_c = \frac{2K_u}{m_s}$,K_u is uniaxial magnetocrystalline anisotropy coefficient.

$H_{int} = I_f S^z e_z$, where, $I_f = \frac{2I_u}{d\, m_s}$, I_u is interface uniaxial anisotropy coefficient which is normal to the free layer.

$H_{ext} = H_e e_z$, where H_e is external applied magnetic field. Here $H_e = 0$.

Rewriting eq (1) for the free layers 1 and 2, we get,

$$\frac{d\vec{S}_1}{dt} + \alpha\vec{S}_1 \times \frac{d\vec{S}_1}{dt} = -\gamma_g\mu_0\vec{S}_1 \times \vec{H}_{eff1} + \gamma_g\, b_j I\left[\vec{S}_1 \times \vec{S}_1 \times (a_1\vec{S}_1 + a_1\vec{S}_2)\right] + \gamma_g\, b_j I\left[\vec{S}_1 \times (b_1\vec{S}_1 + b_1\vec{S}_2)\right] \qquad (2)$$

$$\frac{d\vec{S}_2}{dt} + \alpha\vec{S}_2 \times \frac{d\vec{S}_2}{dt} = -\gamma_g\mu_0\vec{S}_2 \times \vec{H}_{eff2} + \gamma_g\, b_j + \gamma_g\, b_j I\ \ b\left[\vec{S}_2 \times \vec{S}_1\right] \qquad (3)$$

Since free layer is a film $N_x = N_y = 0$ and $N_z = 1$, $D_x = D_y = 0$ and $D_z = -4\pi$. Hence,

$$H_{eff} = D_z S^z e_z + A_c S^x e_x + I_f S^z e_z \qquad (4)$$

The two free layers are antiferromagnetically coupled. The antiferromagnetic coupling is stronger than the coupling between $\vec{S}_0$ and $\vec{S}_1$. Hence we choose the initial configuration as,

$\vec{S}_1 = -\vec{S}_2 = -\vec{e}_z$.

*Runge-Kutta Method***:**

To solve the extended LLGS equation, we have used fourth order Runge-Kutta method. Numerical integration is done taking the components of the eq (2 and 3) in steps of 0.5ns. The calculation is done for fixed free layer of thickness d_1 = 10nm and varying d_2 thickness as 5nm, 10nm, 15nm and 20nm, damping constant $\alpha = 0$, $m_s = 1.15 \times 10^6$ A/m^2, $\gamma = 0.52 \times 10^{-6}$ ms/A. Initially the iteration is done by taking J= 0.1 x 10^{11}A/m^2, $A_c = 0$ and $I_f = 0$. The current density is increased to find the critical value for which the magnetization components switch from its initial value. Then the procedure is repeated first by adding $I_u = 0.89 \times 10^{-3}$ J/m^2 as interface anisotropy and then by introducing K_u= 2 x 10^5 J/m^3 as crystalline anisotropy.

2. RESULTS AND DISCUSSIONS:

The initial orientation of the spins of the free layers F_1 and F_2 are S_1 (001) and S_2 (00-1) which implies they are out of phase with each other. It is intended to investigate the switching dynamics of the spins. Thus iteration is done on the CFL structure with free layers F_1 and F_2 of thicknesses, d_1 and d_2 10 nm with polarisation factor 0.6. The current density J is slowly increased from 0.2 x 10^{11}A/m^2 and the spin configuration is observed to remain the same for lower current values with lapse of time. For current density 1.61 x10^{11}A/m^2 at 5ns, the z component of both the spins S_{1z} and S_{2z} starts to switch gradually from its initial configuration and approaches its reversal at 15ns. This is unlike the regular sharp switching.

Hence for an isotropic layer, the switching occurs for current density 1.61 x10^{11}A/m^2, in duration of 10ns. With additional uniaxial interface anisotropy energy I_F, it is found that switching occur 1.8ns earlier and along with magneto crystalline anisotropy A_C, a further decrease of 1.5ns is observed. Thus the spin relaxes in 6.7 ns, where it took 10ns for an isotropic medium shown in Fig (2).

Figure (3) shows the magnetization trajectories of S_1 and S_2. As the current density increases and reaches the critical value the spin S_1 and S_2 starts to switch but with opposite phase. Spin valve pillar with CFL, shows reduced density for d_1=d_2=10nm. On decreasing the thickness and practically maintaining the thermal stability, the current density can be really decreased further. As reported in [17] the reduction mechanism may be due to the coupling between F_1 and F_2. As a clear picture there may be energy levels for spin waves, when spin polarised current passes through the spin valve, the lowest energy spin waves are being excited even with low current density.

Switching time can be changed by varying the film thickness d_1 and d_2. Since they are directly proportional to each other, as the thickness is reduced switching time also reduces, which is depicted in fig(4). The graph is drawn for d_1=5 nm and various values of d_2. Initially, iteration is done for A_c =0 and I_f =0. Switching time increases as thickness increases as shown in fig(4)a. Then I_f is added in LLGS equation and calculation is repeated and fig (4)b is drawn. Finally A_c is also added and values are plotted as in fig(4)c. The plots a, b and c shows the same increasing fashion, but as anisotropies I_f and A_c are introduced switching time decreases, which is also shown in fig(2). For the thickness of d_2=5 nm all the 3 plots a, b and c shows a drastic decrease, which resembles switching is greatly affected when the thickness is decreased below 10 nm.

Figure (5) shows the variation of critical current density J_c with respect to polarisation factor P. As P increases J_c decreases. For the reduction mechanism of J_c polarisation factor may be increased and thickness of the free layer can be decreased, which implies that P lies in strong interlayer exchange coupling. When spin polarised current flows, S_1 and S_2 are excited. Even though S_1 and S_2 precessions are out of phase with each other, one assists the other and after some time even for small current density switching occurs. Hence strong exchange coupling is the reason for decrease in J_c . Furthermore we have introduced anisotropies I_f and A_c which shows further decrease in J_c as depicted in the fig(5)b and c.

Spin Transfer Torque (STT) induces the precessional motion of magnetization dynamics. There are torque models like ballistic interface torque model and diffusive exchange torque model depending on symmetric or asymmetric structures. To understand the STT contribution to the spin dynamics, graphs are plotted between STT coefficient vs current density as shown in fig(6) and STT coefficient vs polarisation factor P as shown in fig(7) for various values of d_2(5nm, 6nm, 7nm, 8nm). STT coefficient is directly proportional to J_c and P, hence as expected STT coefficient increases as J_c and P increases for all values of d_2. There is a noticeable increase of STT as d_2 decreases.

3. CONCLUSION:

Magnetization dynamics of CFL spin valve structure is studied by solving extended LLGS equation using fourth order Runge-Kutta method. The uniaxial interface anisotropy and crystalline anisotropy lowers the switching time and critical current density. Spin transfer torque coefficient shows a rapid increase as thickness of the free layer decreases and as polarisation factor increases. The study shows that for ultrafast switching to occur for lower current density the CFL spin valve structure of less than 10nm thickness is preferable.

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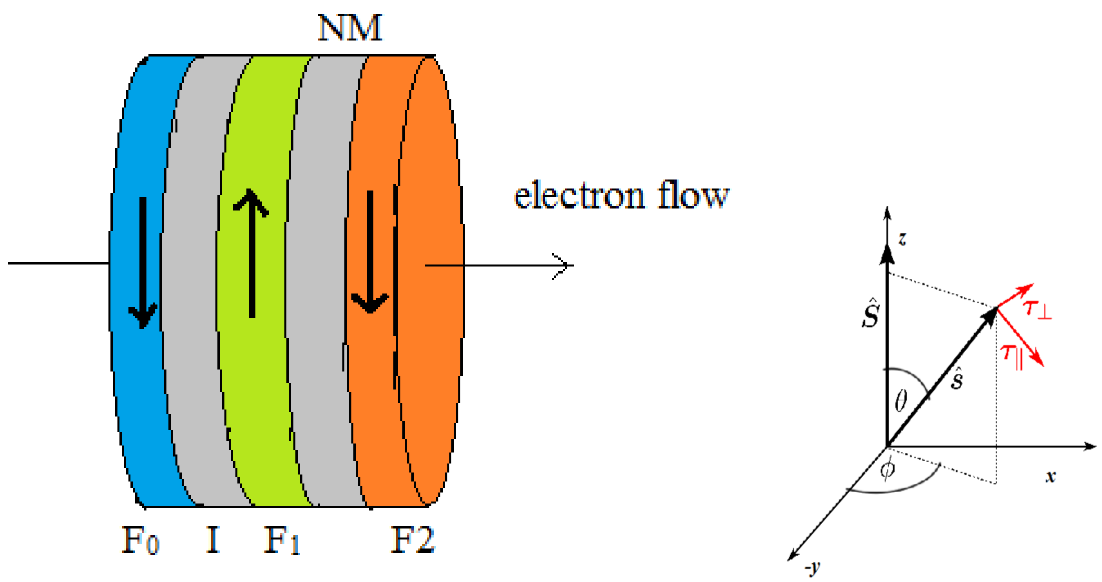

Fig (1) Spin valve pillar with a composite free layer with spherical coordinates of spin S and STT components $\tau_{\parallel}$ and $\tau_{\perp}$.

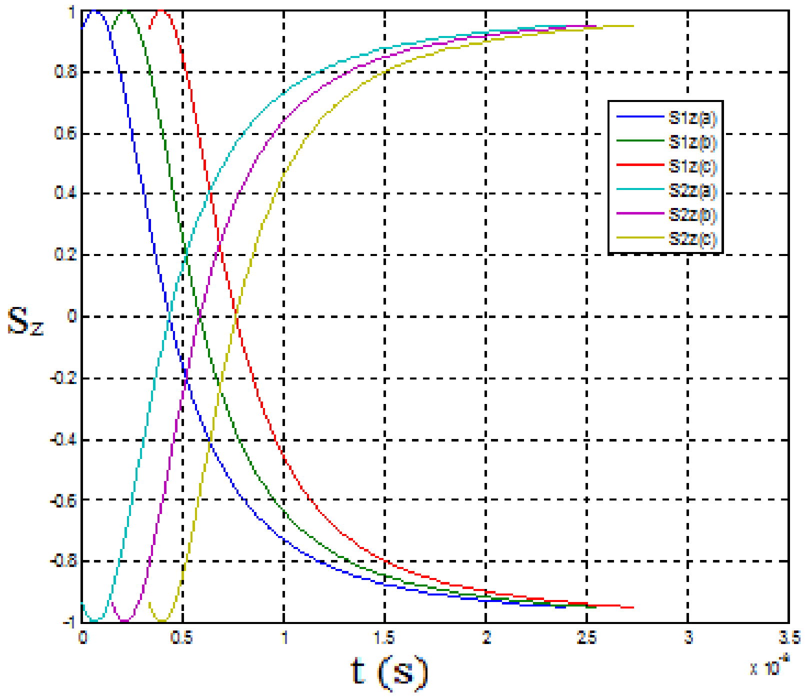

Fig (2). Magnetization reversal of z components of S_1 and S_2.(a) I_f=0 and A_c=0 (b) I_f =0.89 x 10^{-3} J/m^2 and A_c=0 (c) I_f =0.89 x 10^{-3} J/m^2 and $A_c \neq 0$.

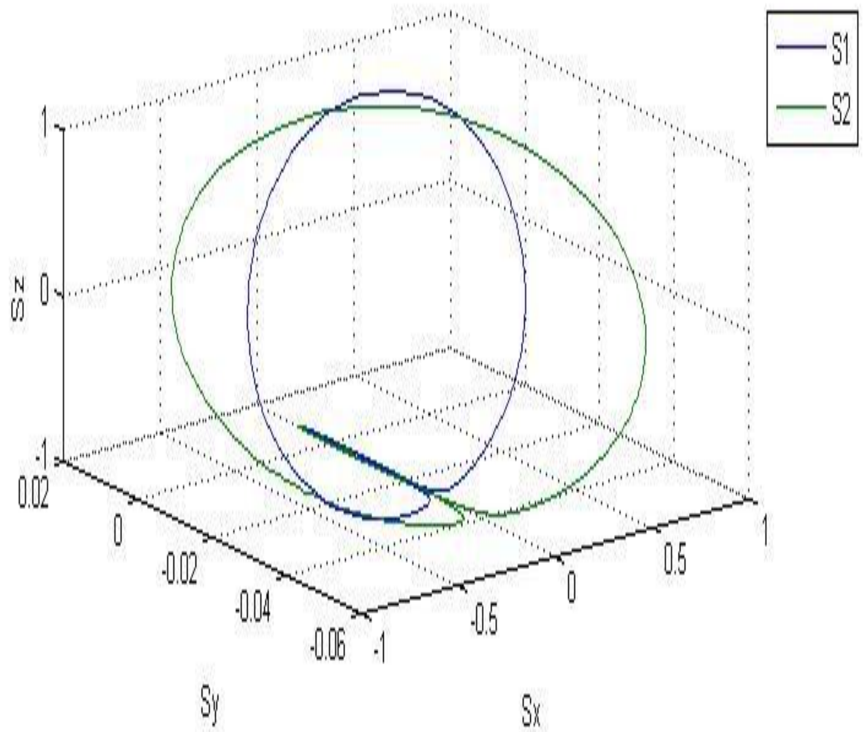

Fig (3) Magnetization trajectories of S_1 and S_2.

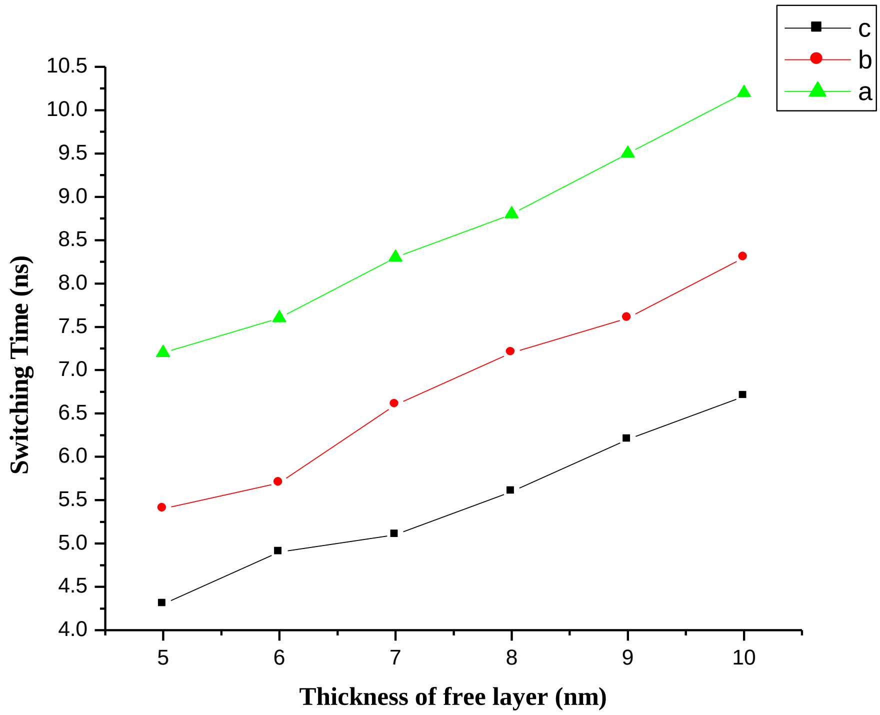

Fig (4) Switching time as a function of thickness of free layer d_2 (d_1=5nm) (a) I_f=0 and A_c=0 (b) $I_f \neq 0$ and A_c=0 (c) $I_f \neq 0$ and $A_c \neq 0$.

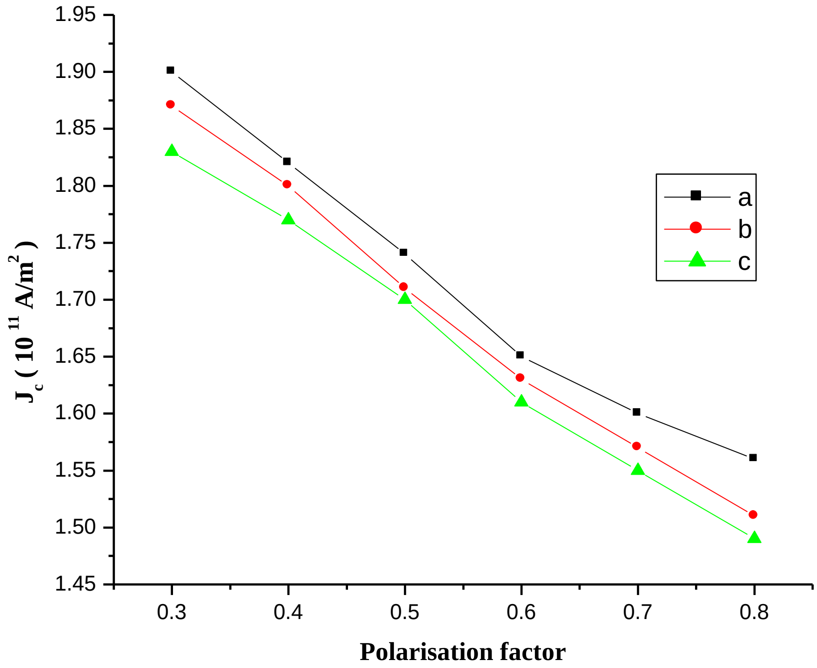

Fig (5) Variation of Critical Current density with Polarisation factor($d_1 = d_2 = 10$nm)
(a) $I_f=0$ and $A_c=0$ (b) $I_f \neq 0$ and $A_c=0$ (c) $I_f \neq 0$ and $A_c \neq 0$.

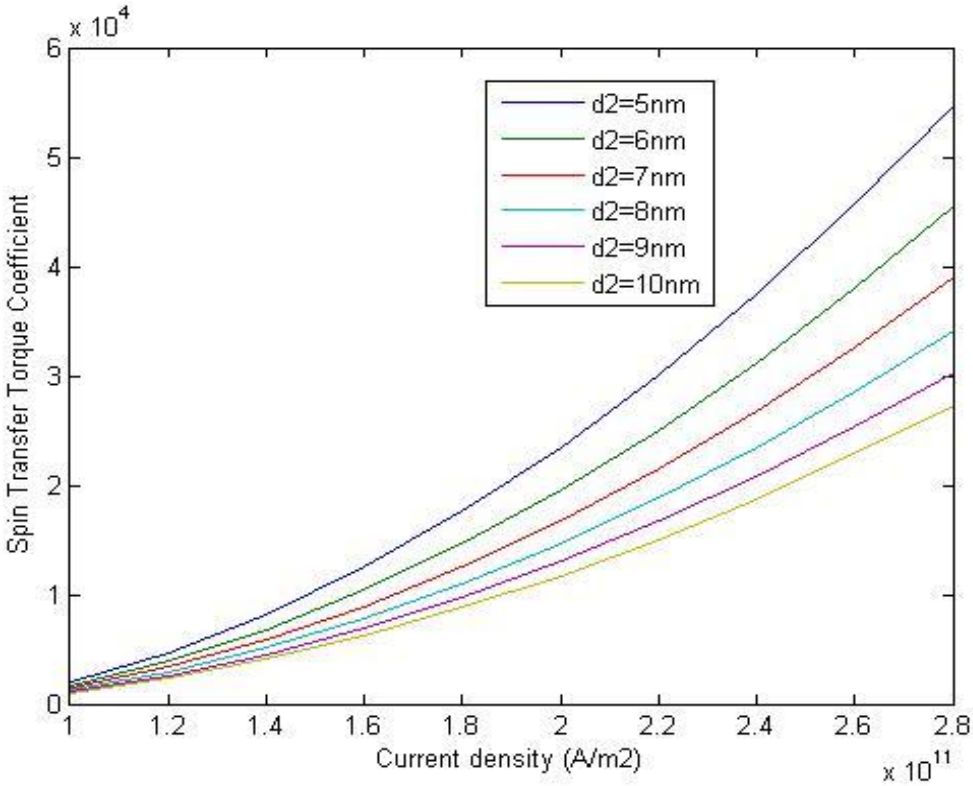

Fig (6) Spin transfer torque coefficient as a function of critical current density for various values of d_2 .

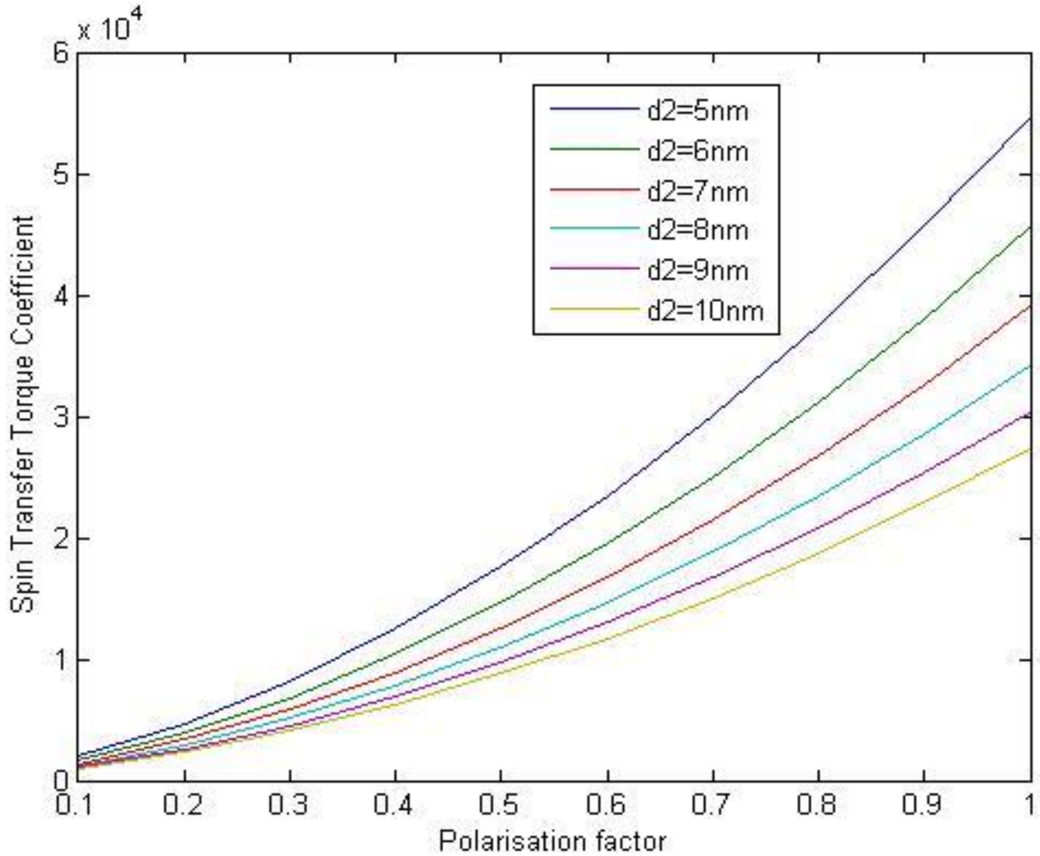

Fig (7) Spin transfer torque coefficient as a function of Polarisation factor for various values of d_2.