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High frequency spin torque oscillators with composite free layer spin valve

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ABSTRACT

We report the oscillations of magnetic spin components in a composite free layer spin valve. The associated Landau–Lifshitz–Gilbert–Slonczewski (LLGS) equation is studied by stereographically projecting the spin on to a complex plane and the spin components were found. A fourth order Runge–Kutta numerical integration on LLGS equation also confirms the similar trajectories of the spin components. This study establishes the possibility of a Spin Torque Oscillator in a composite free layer spin valve, where the exchange coupling is ferromagnetic in nature. In-plane and out-of-plane precessional modes of magnetization oscillations were found in zero applied magnetic field and the frequencies of the oscillations were calculated from Fast Fourier Transform of the components of magnetization. Behavior of Power Spectral Density for a range of current density is studied. Finally our analysis shows the occurrence of highest frequency 150 GHz, which is in the second harmonics for the specific choice of system parameters.

1. Introduction

The analysis on Spin Transfer Torque (STT) in magnetization dynamics has opened many new perspectives in spintronic devices. STT under external field drives the magnetization to stable coherent oscillations which are in the microwave region. This effect is used in Spin Torque Oscillators (STO), that outlook the local oscillators because of its promising features like high operating frequency, tunability, minimal size and relatively easy integration with complementary metal oxide semiconductor technology [1–3]. Now the challenge lies in increasing the oscillation frequency at zero bias field, increasing the output power with narrow spectral line width, operation under low applied current density, optimization of parameters which controls and tunes the frequency of oscillations and most importantly thermal stability and low cost.

At present STO delivers microwave oscillations of less frequency with low output power. Zeng et al. have reported an oscillation frequency of 1.5 GHz at low current density of 5.4×10^5 A/cm^2 with good tunability and maximum power in zero bias STO with MgO based Magnetic Tunnel Junction (MTJ) [4]. Another interesting micromagnetic modeling of double contact STO has been done in patterned magnetic thin films and obtained a frequency of 48.75 GHz with $H=500$ Oe [5]. Many macrospin simulations on MTJ-STO models have been proposed for estimating the performance at device levels [6–8]. And numerical study was also performed on STO to get sustained stable oscillations with perpendicular anisotropy field [9]. Most promising experimental results in modulating the STO signals just by an addition of an a.c to d.c bias have been reported, which could be used for communication and signal processing applications of STO [10]. STO phase is analytically [11,12] and experimentally [13] studied in spin valve comprising of composite free layer and could obtain an oscillation less than 15 GHz but with large current density in the order of 10^8 A/cm^2. Motivated by the above works we search for STO device which could give high frequency oscillations with low current density. Hence we did the micromagnetic simulation of the magnetization dynamics in STO with composite free layer spin valve. The extended LLGS equation is studied for the selected multilayer structure and it is solved using stereographic projection and also confirmed by Runge–Kutta method. The spin configurations are drawn and a clear picture of magnetization dynamics is reported. The device parameters are optimized to yield very high frequency oscillations with low current density.

2. Physical model and LLGS equation

The basic element of an STT-Magnetic Random Access Memory (MRAM) is Magnetic Tunnel Junction (MTJ), which is a sandwich of two ferromagnetic layers separated by a thin nonmagnetic spacer. The magnetization of the pinned layer is fixed and the free layer can be switched between the two states, parallel or anti-parallel to the fixed magnetization direction.

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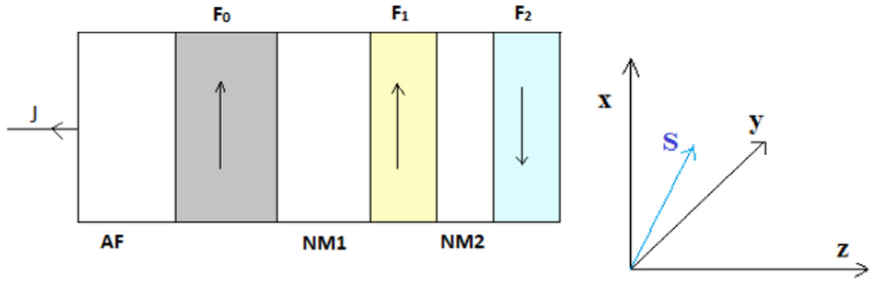

Fig. 1. Spin valve pillar with composite free layer.

In this study we have considered a spin valve pillar as in Fig. 1, with pinned layer F_0 and composite free layers F_1 and F_2 whose unit vectors along the net spin moments are $\hat{S}_0$, $\hat{S}_1$ and $\hat{S}_2$ respectively. Nonmagnetic layers NM1 and NM2 are placed between magnetic layers and the stack is AF/F_0/NM1/ F_1/NM2/F_2, where AF is antiferromagnetic layer, which is responsible for pinning of F_0 (usually IrMn). Spin polarized current is generated when electrons pass through pinned layer. These electrons drift through the NM1 layer and when it enters the free layer it tries to align in the direction of $\hat{S}_1$. There it encounters a torque called spin transfer torque (STT). This torque disturbs the initial configuration of free layers. Moreover there is an exchange interaction called Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction between the magnetizations $\hat{S}_1$ and $\hat{S}_2$ of the free layers. This interaction coupling constant j is positive for ferromagnetic coupling and negative for antiferromagnetic coupling. The value of j can be tuned by varying the spacer thickness [14]. In this study we have taken j as negative (reason will be discussed in Section 5) so that $\hat{S}_1$ and $\hat{S}_2$ are anti-aligned to each other. The initial configuration of the spin vectors are as shown in Fig. 1.

For the micromagnetic simulations we have considered STT as given by Slonczewski. The longitudinal and transverse components of STT can be written as [15],

$$\tau_{\parallel 1} = I\left[\hat{S}_1 \times \hat{S}_1 \times \left(a_1\hat{S}_1 + a_1\hat{S}_2\right)\right] \tag{1a}$$

$$\tau_{\perp 1} = I\left[\hat{S}_1 \times \left(b_1\hat{S}_1 + b_1\hat{S}_2\right)\right] \tag{1b}$$

$$\tau_{\parallel 2} = I\left[a_2\hat{S}_2 \times \left(\hat{S}_2 \times \hat{S}_1\right)\right] \tag{1c}$$

$$\tau_{\perp 2} = I\ b_2\left[\hat{S}_2 \times \hat{S}_1\right] \tag{1d}$$

where 'I' is the current and a_1, b_1, a_2 and b_2 are the system parameters which generally depends on spin current and magnetic configurations. These parameters modifies the amplitude of spin transfer torque and has the form,

$a_i = \frac{\hbar J_y}{2I\ sin\ \Theta}$ and $b_i = \frac{\hbar J_x}{2I\ sin\ \Theta}$ where Θ is the angle between fixed and free layer magnetization, J_x and J_y are components of spin current taken in the non-magnetic side of N/F interface. In the semi classical limit, the LLGS equation for the two free layers can be written as [11,12,14],

$$\frac{d\hat{S}_i}{dt} + \alpha\hat{S}_i \times \frac{d\hat{S}_i}{dt} = \Gamma_i$$

$$\text{and} \quad \Gamma_i = -\gamma_g\mu_0\hat{S}_i \times \vec{H}_{eff} + \gamma_g\, b_j\tau_i \tag{2}$$

where $b_j = \hbar PJ/ed_i m_s$, $i = 1$ and 2, $\vec{H}_{eff}$ 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 $\hat{S}_i$, α is the Gilbert damping constant, b_j is coefficient of spin torque, $\hbar = h/2\pi$, h is Plank's constant, 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, J is current density and P is the polarization factor. The effective field includes,

$$H_{eff} = H_{shape} + H_{ani} + H_{int} + H_{ext} \quad \text{where} \quad H_{shape} = D_x S^x\hat{e_x} + D_y S^y\hat{e_y} + D_z S^z\hat{e_z}$$

$S^x = -4\pi N_x$, $S^y = -4\pi N_y$ and $S^z = -4\pi N_z$ where N_x, N_y, N_z are demagnetization factors and $\hat{e}_x$, $\hat{e}_y$ and $\hat{e}_z$ are unit vectors along x, y and z directions respectively. $H_{ani} = A_c S^x\hat{e}_x$

$A_c = 2K_u/m_s$, K_u is uniaxial magneto crystalline anisotropy coefficient. $H_{int} = I_f S^z\hat{e}_z$,

where $I_f = 2I_u/dm_s$, I_u is surface anisotropy coefficient which is normal to the free layer. $H_{ext} = H_e\hat{e}_z$, where H_e is external applied magnetic field. Here $H_e = 0$.

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

$$\frac{d\hat{S}_1}{dt} + \alpha\hat{S}_1 \times \frac{d\hat{S}_1}{dt} = -\gamma_g\mu_0\hat{S}_1 \times \vec{H}_{eff} + \gamma_g b_j I\left[\hat{S}_1 \times \hat{S}_1 \times (a_1\hat{S}_1 + a_1\hat{S}_2)\right] + \gamma_g b_j I\left[\hat{S}_1 \times (b_1\hat{S}_1 + b_1\hat{S}_2)\right] \tag{3}$$

$$\frac{d\hat{S}_2}{dt} + \alpha\hat{S}_2 \times \frac{d\hat{S}_2}{dt} = -\gamma_g\mu_0\hat{S}_2 \times \vec{H}_{eff} + \gamma_g b_j I\left[a_2\hat{S}_2 \times \left(\hat{S}_2 \times \hat{S}_1\right)\right] + \gamma_g b_j I b_2\left[\hat{S}_2 \times \hat{S}_1\right] \tag{4}$$

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,

$$H_{eff} = D_z S^z\hat{e_z} + A_c S^x\hat{e_x} + I_f S^z\hat{e_z} \tag{5}$$

The extended LLGS Eqs. (3) and (4) is solved using stereographic projection and Runge–Kutta method.

3. Solution for LLGS equation

3.1. Stereographic projection

To reduce the mathematical complexity of the nonlinear LLGS equation, we project the unit sphere of magnetization on to a complex plane. Stereographic projection is a transformation from surface of a sphere to the surface of a complex plane, since the length of the spin vector is preserved. For the transformation, we choose the two variables of the plane to be the real and complex values of a stereographic variable Ω.The components of the spin vectors in term of Ω can be written as,

$$s^x = \frac{\Omega_1 + \Omega_1^*}{1+\Omega_1\Omega_1^*},\ s^y = -i\frac{\Omega_1 - \Omega_1^*}{1+\Omega_1\Omega_1^*},\ s^z = \frac{1-\Omega_1\Omega_1^*}{1+\Omega_1\Omega_1^*},\ \Omega = \frac{s^x + is^y}{1+s^z} \tag{6}$$

The various time and space derivatives of the spin components of Eq. (6) are evaluated and substituted in Eq. (4) and solved as in reference [16]. Finally we arrive at the components of magnetization for both the free layers F_1 and F_2. They are as follows,