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FAST TRACK COMMUNICATION

Ultrafast precessional switching in a permalloy thin film with magnetic surface anisotropy

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Abstract
Analytical and numerical analysis of ultrafast precessional switching dynamics, in a uniformly magnetized anisotropic permalloy thin film, described by the Landau–Lifshitz (LL) equation is presented. Precessional switching is realized in the film by applying a uniform pulsed magnetic field normal to the easy axis of magnetocrystalline anisotropy. The analytical solution of the LL equation is expressed in terms of the Jacobi elliptic function, the period of which is related to the period of the precessional motion. It is shown that switching occurs in the film above a critical value of the applied field. The switching time decreases steadily when the strength of the applied magnetic field is increased and further it reduces significantly when the film has magnetic surface anisotropy in it.

(Some figures in this article are in colour only in the electronic version)

Magnetic recording rapidly approaches the nanometer scale, and in this direction, the critical issue is the manner and speed with which the direction of magnetization can be reversed from one stable configuration to another, preferably using precessional motion. In the conventional switching mechanism, there is only one stable equilibrium configuration after the application of an external magnetic field, namely the reversed state. In this case, switching is a relaxation process towards the stable equilibrium, and hence the damping process is crucial. In the present communication, we use a different switching mechanism known as precessional switching, in which the magnetic torque acting on the magnetization of the medium plays the key role and causes fast precessional motion around the effective field. This drives the magnetization back and forth between the initial and the reversed state. To keep the magnetization in the reversed state, the magnetic field is switched off when reversal is achieved. The duration of the applied magnetic field depends on the amount of switching desired. Thus, in the case of short pulses, the switching properties are governed by the precession of magnetization, and in the case of a long pulsed field, damping assumes importance [1]. In most of the cases, as precessional switching is very fast, the dissipative or damping effect cannot have any significant impact on the switching process within this short duration, and hence it is neglected [2, 3]. The above fact is also verified here numerically, and it is found that damping does not noticeably enhance the speed of the switching. This is because the duration of the pulse in this case is very short. Fassbender and Bauer [1, 4] theoretically observed and experimentally proved that switching in a single-domain ellipsoidal particle is governed by precession in the case of a short pulsed magnetic field, and damping was found to be important in the case of long pulsed magnetic fields. Also, they investigated experimentally the switching dynamics and write endurance of magnetic tunnel junctions, and achieved switching by applying a magnetic field pulse of 250 ps duration [5]. The ripple substrate used in the preparation of exchange coupled systems, such as NiFe/FeMn, enhances anisotropies, still maintaining magnetization switching behavior through coherent rotation [7]. Further, it was shown theoretically that

magnetic damping can be strongly enhanced by implanting Ni ions in NiFe films [6]. In a recent analytical study on precessional switching, based on the solution of the Landau–Lifshitz (LL) equation for uniformly magnetized particles and thin films, Serpico *et al* [8] found that the switching time in these cases is governed by an inverse proportionality law, in agreement with the results of experiments [9]. The above studies also showed that magnetocrystalline and shape anisotropies reduce the switching time by the order of a few nanoseconds. There exists one more useful anisotropy in magnetic systems, known as magnetic surface/interface anisotropy, which was identified by Néel [10]. This occurs whenever symmetry is reduced or broken in the surface/interface, which significantly opposes the demagnetization and hence is expected to change the switching character of thin films significantly. The magnetic surface anisotropy may also be due to the change in composition, structure, surface adsorption and density of electrons in more than one atomic layer in addition to surface roughness [11, 12]. Also, stray fields and strain due to lattice misfit between a single layer and its substrate may contribute to the surface anisotropy through magnetostriction [13, 14]. More often, surface anisotropy also arises due to reduced symmetry of the surrounding surface atoms compared to the bulk. This surface anisotropy, which favors perpendicular magnetization, is more dominant when the thin film measures less than 10 nm.

In the present communication, we explore the impact of magnetic surface anisotropy on the magnetization switching process in a permalloy (NiFe) magnetic film of 5 nm thickness with in-plane magnetocrystalline anisotropy. The investigation is carried out by deriving analytical solution of the governing LL equation, and by numerically solving the equation when the magnetic field is applied normal to the easy axis in the film plane. The associated free energy $h(\mathbf{m})$ is written as

$$h(\mathbf{m}) \equiv h_o = \tfrac{1}{2}[N_x m_x^2 + N_y m_y^2 + N_z m_z^2] - A m_x^2 - B m_y - I m_z^2, \quad (1)$$

where $A = (2A_u/\mu_o m_s^2)$ and $I = (A_p/\mu_o m_s^2 d)$. In equation (1), the terms proportional to N_x, N_y and N_z represent the free energy corresponding to the shape anisotropy which are related to the demagnetization factors along the x, y and z directions of the thin film, respectively. The nanofilm considered here is parallel to the xy plane and hence $N_x = N_y = 0$ and $N_z = 1$. The quantity A_u in the coefficient A represents the magnetocrystalline anisotropy coefficient with the easy axis of magnetization along the x direction and B is the magnitude of the pulsed magnetic field applied along the y direction to reverse the magnetization of the film through coherent rotation [11]. m_s and μ_o are the saturation magnetization of the film and the magnetic permeability of free space, respectively. The last term represents the energy due to magnetic surface anisotropy, in which A_p and d represent the surface anisotropy constant and the thickness of the film, respectively. Unlike magnetocrystalline anisotropy, magnetic surface anisotropy reacts more sensitively to changes in the chemical state of the surface of the film than the magnetic moment [11]. The sign of the magnetic surface anisotropy coefficient A_p, in the case of permalloy thin films, depends on the composition of Ni and Fe. Measurements of A_p in permalloy films indicate that the value is negative when the composition of Ni is below 80%, and only very small positive values close to zero are measured above the composition $Ni_{80}Fe_{20}$ until Ni_{100} [14]. Also, $|A_p|$ decreases with an increase of temperature. The magnetization dynamics of the above system, corresponding to the free energy given in equation (1), is expressed in terms of the following LL equation:

$$\frac{d\mathbf{m}}{dt} = -\gamma[\mathbf{m} \times \mathbf{H}_{\text{eff}}(\mathbf{m})], \quad (2)$$

$$\mathbf{m^2} \equiv m_x^2 + m_y^2 + m_z^2 = 1, \quad (3)$$

where γ is the gyromagnetic ratio and $\mathbf{H}_{\text{eff}}(\mathbf{m})$ is the effective field given by

$$\mathbf{H}_{\text{eff}}(\mathbf{m}) = -[(N_x - 2A)m_x]\mathbf{e}_x + [B - N_y m_y]\mathbf{e}_y + [(2I - N_z)m_z]\mathbf{e}_z. \quad (4)$$

Here $\mathbf{e}_x$, $\mathbf{e}_y$, $\mathbf{e}_z$ represent the unit vectors along the x, y and z axes, respectively.

The dynamical system described by equation (2) admits two integrals of motion, representing conservation of the initial energy h_o and the magnetization as given in equations (1) and (3), respectively. The components of the magnetization, m_x, m_y and m_z, can be obtained by using the above two integrals of motion and one of the component equations of the LL equation. On solving equations (1) and (3) algebraically through appropriate combinations, we obtain the following values of m_x^2 and m_z^2 in terms of m_y:

$$m_x^2 \equiv P_x(m_y) = (2/N_1)[(N_2/2) - Bm_y - (N_3/2)m_y^2], \quad (5)$$

$$m_z^2 \equiv P_z(m_y) = (2/N_1)[(N_4/2) + Bm_y - (N_5/2)m_y^2], \quad (6)$$

where $N_1 = [N_z - 2A - 2I]$, $N_2 = [N_z - 2I - 2h_o]$, $N_3 = [N_z - N_y - 2I]$, $N_4 = [2h_o - N_x - 2A]$ and $N_5 = [N_y - N_x - 2A]$. We find m_y, by solving the m_y component LL equation $dm_y/dt = -N_1 m_x m_z$ after substituting the values of m_x and m_z from equations (5) and (6), and by integrating the resultant equation. The result is

$$\int \frac{dm_y}{\sqrt{P_x(m_y)P_z(m_y)}} = -N_1 \int_0^T dt, \quad (7)$$

which upon evaluation can be expressed in terms of the Jacobi elliptic function, the derivation of which depends on the nature of the following roots $a_\pm$ and $b_\pm$ of the polynomial $P_x(m_y)$ and $P_z(m_y)$:

$$a_\pm = (-B/N_3) \pm \sqrt{(B^2/N_3^2) + (N_2/N_3)}, \quad (8)$$

$$b_\pm = (B/N_5) \pm \sqrt{(B^2/N_5^2) + (N_4/N_5)}. \quad (9)$$

Here, the roots a_- and b_- are the lower extrema, and a_+ and b_+ are the upper extrema. The allowed values of m_y, then lie between the above lower and upper extremum values. As the polynomials $P_x(m_y)$ and $P_z(m_y)$ are proportional to m_x^2 and m_z^2, respectively (see equations (5) and (6)), only those values of m_y that make the polynomials positive are allowed.

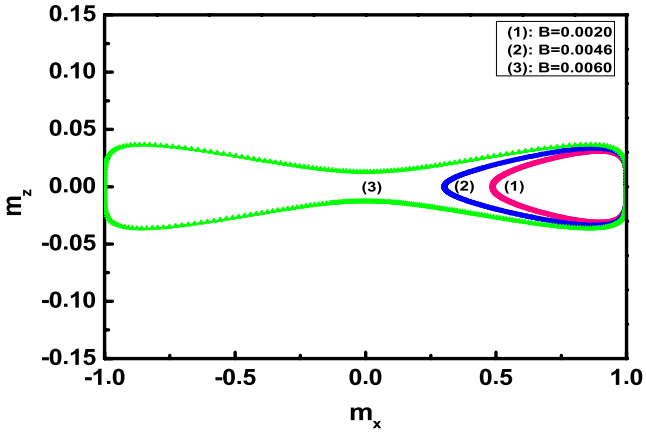

Figure 1. Magnetization trajectories for precessional motion in the (m_x–m_z) plane (equations (5) and (6)) for different values of the external field B below and above $B_{\rm crit}$. Curve (1): $B = 0.0020$; curve (2): $B = 0.0046$; curve (3): $B = 0.006$.

When the magnetization is initially along the easy axis of magnetization, we have $m_x = 1$, $m_y = m_z = 0$, and in this case the value of the initial energy h_o in equation (1) becomes $(N_x - 2A)/2$. Consequently, the values of the upper extrema a_+ and b_+ become positive. Since the lower extrema a_- and b_- are less than and equal to zero, respectively, we concentrate on the upper extrema only. For the above initial conditions, the allowed values of m_y, for low values of the applied field, lie in the range $[0, b_+]$, and at high fields, m_y takes the values in the range $[0, a_+]$. Thus, we have two different situations and we can switch from one to the other when the externally applied magnetic field exceeds the critical value $B_{\rm crit} = N_5/2$, which can be obtained by equating the values of a_+ and b_+. In this case, m_y is constrained to vary between the values 0 and a_+, and even though m_x vanishes, switching can still occur. On the other hand, when $B \leqslant B_{\rm crit}$, even though m_x is always positive, since m_y now lies in the interval 0 and b_+, switching does not occur. For the experimentally measured values [2] given by $A_u = -2 \times 10^3$ J m^{-3}, $\mu_o = 1.257 \times 10^{-6}$ J A^{-2} m^{-1} and $m_{\rm s} = 795$ kA m^{-1}, the critical value of the magnetic field is calculated as $B_{\rm crit} = 0.005$.

We proceed further to find the explicit form of the analytical solution representing the magnetization precession by substituting the values of m_x and m_z from equations (5) and (6) in equation (7) and obtain

$$N \int_{y(0)}^{y(\tau)} \frac{{\rm d}y'}{\sqrt{Y(y')}} = \pm\tau, \tag{10}$$

where $Y(y') \equiv Y(m_y) = (m_y - a_+)(m_y - a_-)(m_y - b_+)(m_y - b_-)$, $\tau = (T/2)\sqrt{N_3 N_5 (b_+ - b_-)(a_+ - a_-)}$ and $N = (1/2)\sqrt{(b_+ - b_-)(a_+ - a_-)}$. The value of the integral on the left-hand side of equation (10) is expressed in terms of the Jacobi elliptic function $sn(\tau; k)$ as

$$N \int_{b_-=0}^{y(\tau)} \frac{{\rm d}y'}{\sqrt{Y(y')}} = sn^{-1}\left(\sqrt{\frac{(a_+ - a_-)(y' - b_-)}{(a_+ - b_-)(y' - a_-)}}, k\right), \tag{11}$$

where $k^2 = (a_+ - b_-)(b_+ - a_-)/(b_+ - b_-)(a_+ - a_-)$ and k is its modulus. Using the above result in equation (10), we obtain

$$m_y(\tau) = -a_+ a_- sn^2(\tau; k)/[(a_+ - a_-) - a_+ sn^2(\tau; k)]. \tag{12}$$

Knowing m_y, it is straightforward to derive the components m_x and m_z using equations (5) and (6). The components of magnetization exhibit periodic motion, with the period of oscillation governed by the complete elliptic integral of the first kind:

$$K(k) = \int_0^1 [(1 - y'^2)(1 - k^2 y'^2)]^{-\frac{1}{2}}\, {\rm d}y'. \tag{13}$$

The period of the precessional motion of magnetization is one-quarter of the period of the Jacobi elliptic function and it is obtained by comparing equations (10) and (11) as

$$T = 8K(k)[N_3 N_5 (b_+ - b_-)(a_+ - a_-)]^{-\frac{1}{2}}. \tag{14}$$

As k is the modulus of the complete elliptic integral $K(k)$, the switching time $T_{\rm s}$, which is actually the time interval during which the magnetization vector precesses between its initial orientation and the reversed direction, can be given as half of the time period T, i.e. $T_{\rm s} = T/2$. The magnetization will remain in the reversed direction, if the field is switched off exactly at that time. Of course, the value of the externally applied magnetic field should be above the critical value $B_{\rm crit}$; otherwise, switching cannot happen. In order to substantiate the statement that the switching is possible only above the critical field, in figure 1, we have plotted the magnetization trajectories $m_x(t)$ and $m_z(t)$ during precessional motion for different values of the external magnetic field, namely $B = 0.002, 0.0046$ and 0.006, which are both below and above the critical value. In the figure, trajectory (3) corresponds to $B = 0.006$, which is above the critical value, and the remaining two trajectories (1) and (2), correspond to the case when $B < B_{\rm crit}$. Trajectory (3) differs drastically from the other two. This trajectory exhibits reversal of the magnetization from the initial state of $\boldsymbol{m} = (1, 0, 0)$ to the reversed state $m = (-1, 0, 0)$. When $B < B_{\rm crit}$, the magnetization trajectories are confined to the positive m_x quadrant, thus proving the absence of switching in these cases. Figure 2 shows a comparison of reversed magnetization trajectories for an applied field value of $B = 0.006$ in the case of the film with and without magnetic surface anisotropy.

The above analytical result on magnetization switching is also confirmed by numerically integrating equation (2) through forward iteration in space, using a Runge–Kutta (RK) procedure for the same set of parameter values. The resultant magnetization curves exactly coincide with the analytical plots in figures 1 and 2. In figure 2, the state of magnetization m_x, which was originally along the positive direction, is reversed in both cases. Further, there is a change in the curvature of the upper half of the magnetization trajectory, due to reduced symmetry, when surface anisotropy is present in the film, which indicates that the magnetization component m_x reverses very quickly from the positive to negative region, and the same is also reflected in the switching time.

The switching time for reversal of magnetization is calculated numerically by solving the m_x-component LL

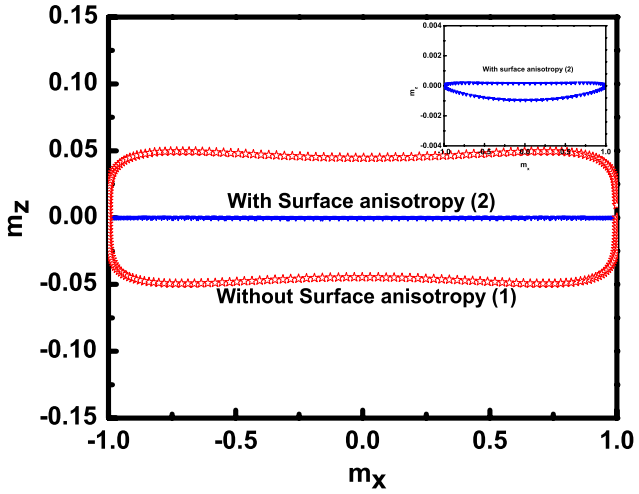

Figure 2. Magnetization trajectories for precessional motion in the (m_x–m_z) plane when $B = 0.006$. The parameters [2, 11] used are $A_p = -0.1 \times 10^{-3}$ J m^{-2}, $A_u = -2 \times 10^3$ J m^{-3}, $\mu_o = 1.257 \times 10^{-6}$ J A^{-2} m^{-1} and $m_s = 795$ kA m^{-1}. Curves (1) and (2) represent the magnetization trajectories in the absence and in the presence of surface anisotropy, respectively. The inset in the figure represents the zoomed magnetization trajectory 2 (along the m_z axis), when there is surface anisotropy in the film. While curve (1) is symmetric, curve (2) looks asymmetric because of the presence of surface anisotropy in the film, which is due to reduced/broken symmetry in the surface that reduces the switching time due to reduction in the path length of the trajectory.

equation (2) by iterating forward in time, using the RK method with the initial condition $\mathbf{m} = (1, 0, 0)$ for the same set of parameter values and field. The applied magnetic field is switched off precisely at the time of iteration, when the m_x component reaches the value of -1. The results are plotted as m_x against T_s which is rescaled in units of 10^{-9} in figures 3(a) and (b), corresponding to the cases when surface anisotropy is absent and present, respectively. The arrows in both the figures schematically represent coherent rotation of the m_x component of magnetization towards switching. The projection of CD and EF on the T_s axis represent the switching time in both the cases. The calculated values from the figures show that the switching time reduces from 52 to 0.460 (in units of 10^{-9}) when surface anisotropy is introduced. However, the analytically calculated values of the switching time using equation (14) are 60 and 0.468 (in units of 10^{-9}) in the absence and presence of surface anisotropy, respectively. The small difference that occurs in the case of analytical and numerical values of switching time is due to the fact that the analytic value of the period is computed for the specific value of the modulus $k = 0$.

In the above, while calculating the switching time, we treated the critical field as a dimensionless quantity. Now, to verify our results with that of simulation and experiments, we first express the value of the critical field $B_{crit} = 0.005$ in units of kA m^{-1}, which is equivalent to 3.975 kA m^{-1}. The above value is in very close agreement with the experimentally reported critical field value (4 kA m^{-1}) of Schumacher *et al* [15]. The numerical calculation of the switching time is repeated for different values of the applied magnetic field in steps of 5 kA m^{-1} starting from 5 kA m^{-1} (i.e. above the critical field of 4 kA m^{-1}) and going up to 50 kA m^{-1}. Figures 4(a) and (b) are the plots of the results showing the behavior of switching time when there is no surface anisotropy in the film and in the case of the film with surface anisotropy, respectively. From the figures, one observes that the magnetization switching time reduces when the strength of the applied magnetic field is increased. The surface anisotropy reduces the switching time significantly, which is evidently seen from figures 4(a) and (b). For instance, when the applied magnetic field is 10 kA m^{-1}, the switching time from figures 4(a) and (b) is measured to be 325 ps and 125 ps, respectively. The reason for this significant reduction in switching time due to surface anisotropy is because of the reduced path length for reversal, which is due to broken/reduced symmetry in the surface of the film. The values of the switching time we have found for different field strengths in the present communication closely agree with the values computed analytically by d'Aquino *et al* [2] in the case of NiFe thin film.

In conclusion, it is established that efficient magnetic switching occurs in permalloy thin films under the joint influence of different anisotropies and an externally applied magnetic field above a critical value. In particular, magnetic surface anisotropy reduces the magnetization switching time significantly. This is due to reduced/broken symmetry in the

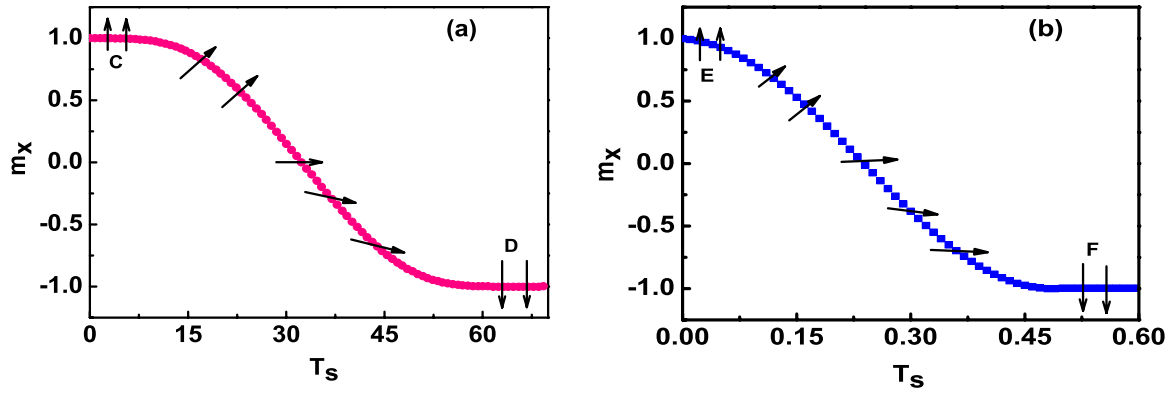

Figure 3. Switching curves: coherent rotation of spins for an applied field $B = 0.006$. (a) Switching curve when surface anisotropy is absent. (b) Switching curve when there is surface anisotropy. The projection of CD and EF on the T_s axis represent the switching time in both the cases.

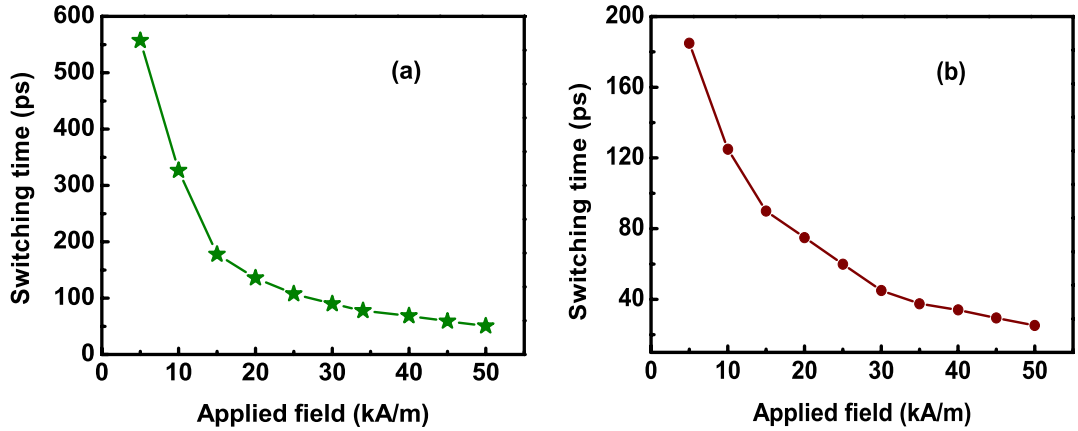

Figure 4. Switching time as a function of applied field: the strength of the magnetic field is varied from 5 to 50 kA m^{-1} in steps of 5 kA m^{-1}. (a) Behavior of switching time, when there is no surface anisotropy in the film. (b) Behavior of switching time, when there is surface anisotropy in the film.

surface of the film, which reduces the path length of the trajectory for reversal.

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