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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.

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 mismatch 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 $h(m)$ is written as

$$h(m) = h_0 = \frac{1}{4}[N_x m_x^2 + N_y m_y^2 + N_z m_z^2]$$

$$- A m_x^2 - B m_y - C m_z^2,$$

where $A = (2A_c/\mu_s m_0^2)$ and $I = (A_p/\mu_s m_0^2 d)$. 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 $x$-$y$ plane and hence $N_x = N_y = 0$ and $N_z = 1$. The quantity $A_p$ 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 $\mu_s$ 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$_{75}$Fe$_{25}$ [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:

$$\frac{dm}{dt} = -\gamma [m \times H_{\text{eff}}(m)],$$

$$m^2 = m_x^2 + m_y^2 + m_z^2 = 1,$$

where $\gamma$ is the gyromagnetic ratio and $H_{\text{eff}}(m)$ is the effective field given by

$$H_{\text{eff}}(m) = -[(N_y - 2A)m_x]e_x + [(B - N_a)m_y]e_y$$

$$+ [(2I - N_z)m_z]e_z.$$

Here $e_x$, $e_y$, and $e_z$ 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 $h_0$ 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 $m_y^2$ in terms of $m_z$:

$$m_x^2 \equiv P_x(m_z) \equiv (2/N_z)\{(N_x/2) - B m_x - (N_y/2)m_y\},$$

$$m_y^2 \equiv P_y(m_z) \equiv (2/N_z)\{(N_x/2) + B m_x - (N_y/2)m_y\},$$

where $N_1 = [N_x - 2A - 2I]$, $N_2 = [N_x - 2I - 2h_a]$, $N_3 = [N_y - N_z - 2I]$, $N_4 = [2h_o - N_x - 2A]$ and $N_5 = [N_y - N_z - 2A]$. We find $m_z$, by solving the $m_z$ component LL equation $dm_z/dt = -[N_0 m_x m_z]$, after substituting the values of $m_x$ and $m_y$ from equations (5) and (6), and by integrating the resultant equation. The result is

$$\int \frac{dm_z}{\sqrt{P_x(m_z)P_y(m_z)}} = -N_1 \int_0^T dt,$$

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 $P_x(m_z)$ and $P_y(m_z)$:

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

$$b_\pm = (B/N_3) \pm \sqrt{(B^2/N_3^2) + (N_2/N_3)}.$$

Here, the roots $a_-$ and $b_-$ are the lower extrema, and $a_+$ and $b_+$ are the upper extrema. The allowed values of $m_z$, then lie between the above lower and upper extremum values. As the polynomials $P_x(m_z)$ and $P_y(m_z)$ are proportional to $m_x^2$ and $m_y^2$, respectively (see equations (5) and (6)), only those values of $m_z$ that make the polynomials positive are allowed.
When the magnetization is initially along the easy axis of magnetization, we have \( m_\perp = 1, m_\parallel = m_\pm = 0 \), and in this case the value of the initial energy \( h_0 \) in equation (1) becomes \( (N_\perp - 2A)/2 \). 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 \( m_{\parallel} \), for low values of the applied field, lie in the range \([0, b_+]\), and at high fields, \( m_{\parallel} \) 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 \( B_{\text{crit}} = N_\parallel/2 \), which can be obtained by equating the values of \( a_+ \) and \( b_+ \). In this case, \( m_{\parallel} \) is constrained to vary between the values 0 and \( a_+ \), and even though \( m_{\parallel} \) vanishes, switching can still occur. On the other hand, when \( B < B_{\text{crit}} \), even though \( m_{\parallel} \) is always positive, since \( m_{\perp} \) now lies in the interval 0 and \( b_+ \), switching does not occur. For the experimentally measured values [2] given by \( A_0 = -2 \times 10^7 \text{ J m}^{-3}, \mu_0 = 1.257 \times 10^{-6} \text{ J A}^{-2} \text{ m}^{-1} \), and \( m_\perp = 795 \text{ kA m}^{-2} \), the critical value of the magnetic field is calculated as \( B_{\text{crit}} = 0.005 \).

We proceed further to find the explicit form of the analytical solution representing the magnetization precession by substituting the values of \( m_{\parallel} \) and \( m_{\perp} \) from equations (5) and (6) in equation (7) and obtain

\[
N \int_{y(0)}^{y(\tau)} \frac{dy'}{\sqrt{Y(y')}} = \pm \tau, \tag{10}
\]

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

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

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

\[
m_{\parallel}(\tau) = -a_+ a_- s_\perp^2(\tau)/[a_+ - a_-]sn^2(\tau; k). \tag{12}
\]

Knowing \( m_{\parallel} \), it is straightforward to derive the components \( m_\parallel \) and \( m_\perp \) 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:

\[
K(k) = \int_0^1 [(1 - y'^2)(1 - k^2 y'^2)]^{-1/2} dy'. \tag{13}
\]

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

\[
T = 8K(k)[N_\parallel N_\perp(b_+ - b_-)(a_+ - a_-)]^{-1}. \tag{14}
\]

As \( k \) is the modulus of the complete elliptic integral \( K(k) \), the switching time \( T_s \), 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., \( T_s = T/2 \). 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 \( B_{\text{crit}} \); 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 curves exactly coincide with the analytical plots of magnetization exhibit periodic motion, with the period of

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Magnetization trajectories for precessional motion in the \((m_\perp, m_\parallel)\) plane (equations (5) and (6)) for different values of the external field \( B \) below and above \( B_{\text{crit}} \). Curve (1): \( B = 0.0020 \); curve (2): \( B = 0.0046 \); curve (3): \( B = 0.0060 \).
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$^{-3}$, $A_u = -2 \times 10^3$ J m$^{-3}$, $\mu_0 = 1.257 \times 10^{-6}$ 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 $m = (1, 0, 0)$ for the same set of parameter values and field. The applied magnetic field is switched off precisely at the time of iteration, when the $m_z$ component reaches the value of $-1$. The results are plotted as $m_z$ 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 $m_z$ 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 $B_{\text{crit}} = 0.005$ 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
surface of the film, which reduces the path length of the trajectory for reversal.

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