

## LLG STUDY OF THE PRECESSIONAL SWITCHING PROCESS IN PULSED MAGNETIC FIELDS

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In this paper we are presenting the results of our micromagnetic studies concerning the precessional switching process of the magnetic moment in the presence of a pulsed magnetic field. The magnetization dynamic is calculated with the well-known Landau-Lifshitz-Gilbert equation. We have analyzed the effect of pulse duration and the effects induced by the moment orientation dependent damping term. The results are discussed and compared with the results presented by other authors.

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### 1. Introduction

One of the most exciting research area in the domain of magnetic recording is related to the switching time of the magnetic moment. The fast precessional magnetization switching in thin films is seen as a possibility to increase the speed of magnetic recording and, as a consequence, recently, many studies were dedicated to this phenomenon. In this process, as the name is suggesting, the magnetic moment precession has an essential role in the switching of the magnetic moment from one free energy minimum to another. This switching process can be produced faster and using a smaller field than the classical switch.

Obtaining reproducible magnetization switching within the sub-nanosecond regime and the sub-micron range is currently one of the most challenging tasks of nanomagnetism [1]–[7]. An intense research activity is currently in progress for measuring [7-9] and for numerically simulation [10] the ultrafast dynamics of the magnetization in nanomagnets. Lately, the fast precessional magnetization switching in thin magnetic films has been the focus of considerable research. The switching has been studied experimentally [2-4] and also simulated using the Landau – Lifshitz – Gilbert (LLG) equation [6].

The purpose of this paper is to present a numerically simulation of the precessional switching in pulsed magnetic field based on the LLG equation and to compare the results with the experimental data [4]. We will refer for simplicity to a thin film element with in-plane anisotropy (see Fig. 1).

The magnetization is initially along the easy axis of the thin film (Ox axis, Fig.1). The switch of magnetization is caused by a pulsed magnetic field ( $H_i$ ) applied orthogonal to the easy axis in the film plane. If the field is strong enough, the magnetization is moved away from its initial state due to the torque produced by this magnetic field. The trajectory of precessional motion is very sensitive to the field amplitude and duration, and the magnetic moment does not significantly relax during the application of the field. After the field is switched off, the magnetic moment starts a relaxation dynamics toward the equilibrium position. Magnetization reversal occurs if the field is

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switched off when the precessional movement has brought the magnetic moment close to its reversed orientation.

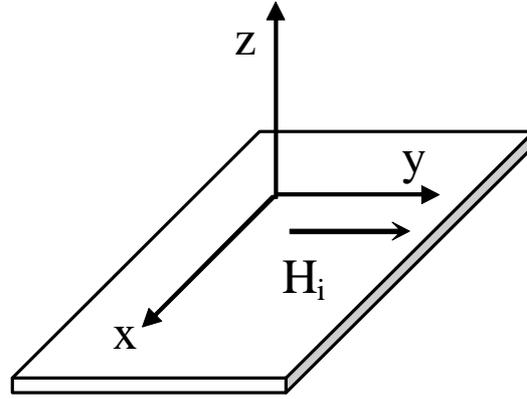


Fig. 1. Magnetic thin film subject to in-plane applied field. The anisotropy axis is along the Ox axis.

## 2. Magnetic moment dynamics

The dynamic of the magnetic moment is described by the Landau-Lifshitz-Gilbert (LLG) equation written as [11-13]:

$$\frac{d\vec{m}}{dt} - \alpha \vec{m} \times \frac{d\vec{m}}{dt} = -\vec{m} \times \vec{h}_{eff}(\vec{m}) \quad (1)$$

where  $\vec{m} = \vec{M} / M_s$ ,  $\vec{h}_{eff} = \vec{H}_{eff} / M_s$  (normalized effective field), time is measured in unit of  $1/(\mu_0 \gamma M_s)$ ,  $M_s$  is the saturation magnetization,  $\gamma$  is the gyromagnetic ratio and  $\alpha$  is the damping parameter. The effective field applied to each magnetic entity within the thin film is given by:

$$\vec{h}_{eff}(m) = (Km_x - h_x)\vec{u}_x + h_y\vec{u}_y - m_z\vec{u}_z \quad (2)$$

where  $\vec{u}_x$ ,  $\vec{u}_y$  and  $\vec{u}_z$  are the versors of the cartesian axes x, y and z,  $K$  is the anisotropy constant,  $h_x$  and  $h_y$  are the projection of the applied magnetic field (constant during the pulse duration) on the x and respectively y axes [11]. The magnetic free energy equivalent to the effective field (2) is:

$$E(m) = -\frac{1}{2}Km_x^2 + \frac{1}{2}m_z^2 + h_xm_x - h_y m_y \quad (3)$$

For  $h_x = h_y = 0$ , the LLG equation (1) has six critical points: two stable equilibrium points  $F_1^\pm$  with  $\vec{m} = \pm\vec{u}_x$ , two saddle points  $S_2^\pm$  with  $\vec{m} = \pm\vec{u}_y$  and two unstable equilibrium points  $F_3^\pm$  with  $\vec{m} = \pm\vec{u}_z$  [13]. One can use a stereographic projection (the plane  $(w_1, w_2)$  with  $w_1 = m_x/(1+m_z)$  and  $w_2 = m_y/(1+m_z)$ ) to show both the free energy graph and the moment trajectory (see Figs. 2a and 2b).

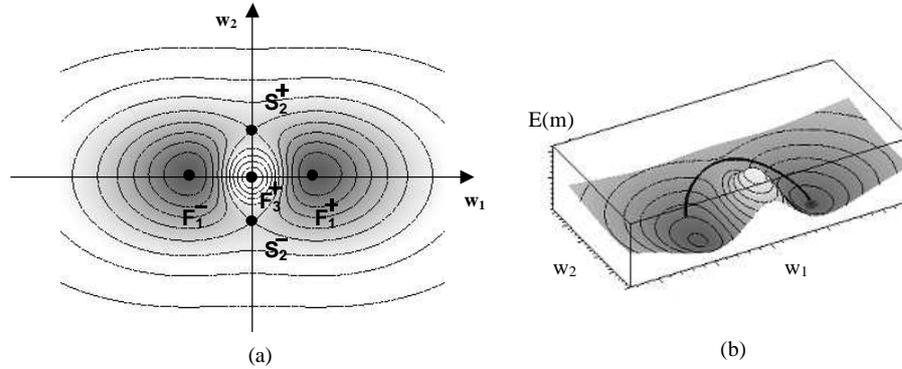


Fig. 2. The phase portrait in the stereographic plane. a) The free energy; b) Moment trajectory.

The shaded regions in Fig. 2(a) mark the areas where the magnetic free energy is below the energy of the saddle points  $S_2^\pm$ , while in the white regions the energy is above the energy of the saddle points. When the magnetic moment motion starts in white regions, then, depending on initial conditions it may relax to one of the two stable points  $F_1^\pm$ . The applied field pulse tilts magnetization outside the magnetic film plane. Then a strong vertical demagnetizing field forces the magnetization to rotate in the film plane [10]. When the precession brings magnetization from one shaded region to another 2(b), the applied field is switched off. Then, as a function of the value of the damping parameter, the magnetic moment relaxes to the new equilibrium position [13].

**3. Simulation results**

In the numerical simulations of the precessional motion trajectory of the magnetic moment and the switching probability we have considered  $\gamma = 56\pi$  GHz/T,  $\alpha = 0.03$ , the anisotropy field  $H_k = 22$  kA/m, the saturation magnetization  $M_s = 1079$  kA/m. A small additional field  $H_a = 3$  kA/m was added, antiparallel with  $H_k$  in order to simulate the exact conditions of the experiments presented in [4]. If during the first oscillation circle one applies a short pulse, which is turned off when the magnetization is near the opposite direction relatively to the initial state, this will cause the switch of magnetization. In Fig. 3(a) it is shown the trajectory of magnetic moment for this case (point A is the initial magnetization direction, point B is where the pulse field is turned off and C is the point of equilibrium state). A slightly longer field pulse will allow the magnetic moment to rotate back towards the initial state, resulting in a no-switch event after the field pulse ends (Fig. 3(b) - point A' is the initial magnetization direction, point B' is where the pulse field is turn off and taking into account there is no-switch the system will relax in the initial state A').

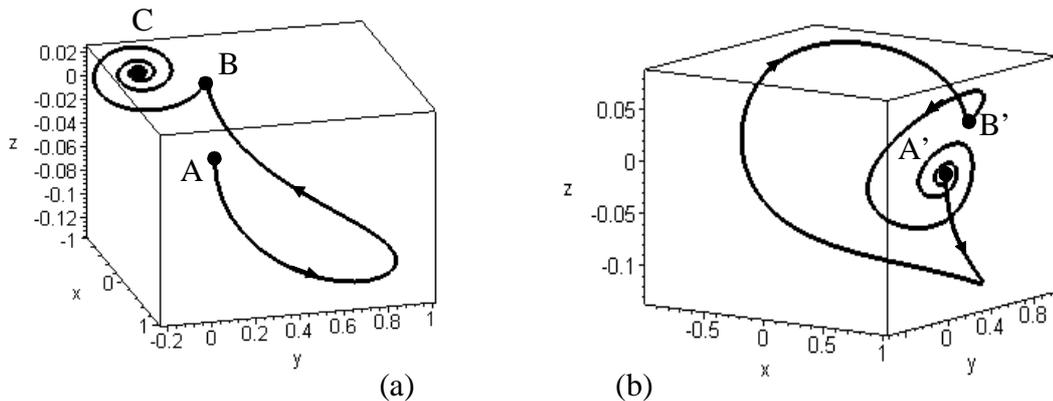


Fig. 3. Trajectory of the magnetic moment which follows the direction given by the arrows.

The LLG simulations are deterministic in essence, so starting from the same initial state we shall always arrive in the same final state. However, experiments show that there is a certain probability for the particle switch that depends on various factors. To include that in our model we have generated random initial states (as a model for the real situation in which thermal effects produce such a dispersion of the initial state position when the pulse is applied to the sample). Generating a number of initial states, one observes that, as observed in the experiment, that only a percentage of the particles have a switch. The switch probability is calculated as the ratio between the switch moments over the total number of numerical experiments.

Fig. 4(a) shows the switching probability as a function of the duration of the field pulse. One can observe that the switching probability decreases to zero when the pulse duration is increased. If the amplitude of the field pulse is increased, then the probability of switching is greater for the short pulse field.

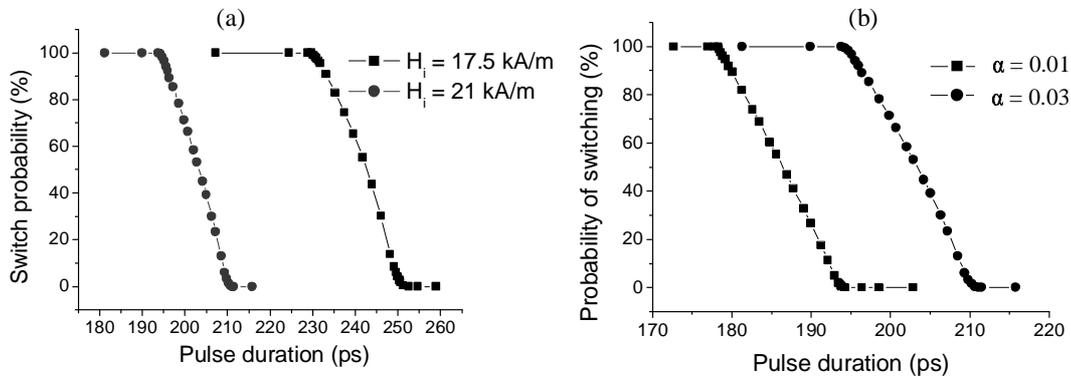


Fig. 4. Switch probability vs. pulse duration and as a function of the pulse field amplitude (a) and as a function of the damping parameter  $\alpha$  (b).

We have also analysed the dependence of the switch probability on the damping parameter  $\alpha$ . From Fig. 4(b) one may observe that, for a smaller  $\alpha$ , the probability of switching decreases for longer pulse fields. This can be explained by the fact that if  $\alpha$  is smaller, right hand side term in the LLG equation (1), which describes the precessional motion, becomes more important than the damping term, so, the magnetization precession become more faster.

The switch of magnetization can also be obtained when  $H_a$  is applied antiparallel to the direction of initial magnetization, as well as parallel to this direction [3]. Figure 5 shows that the switching probability is also depending on the amplitude of the magnetic field applied along the easy axis. We have considered that the applied magnetic field is opposite to the initial magnetization direction. The minimum time to reach the equilibrium position after switch occurs ( $T_c$ ) corresponds to one half period of the first oscillation circle (see Fig. 6) when the magnetic moment has the nearest position to the equilibrium position in the switch state.

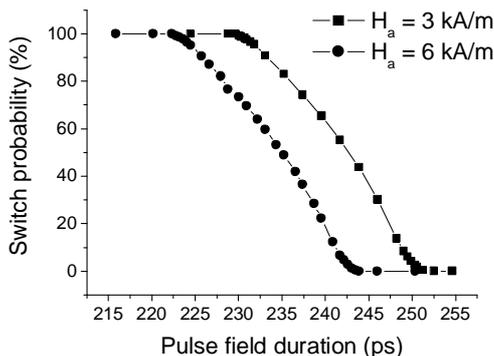


Fig. 5. Probability of switching as a function of the additional applied field. The amplitude of the pulse field is  $H_i = 17.5$  kA/m and  $\alpha = 0.03$ .

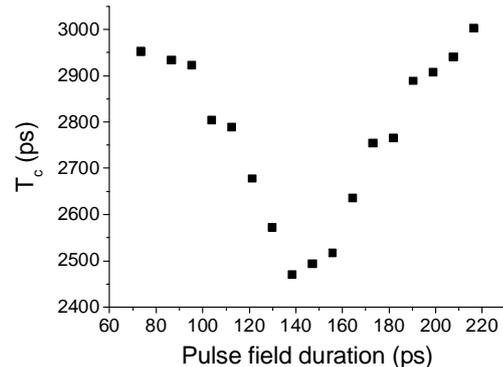


Fig. 6. The minimum time to reach the equilibrium position vs. pulse field duration. The amplitude of the pulse field is  $H_i = 17.5$  kA/m and  $\alpha = 0.03$ .

#### 4. Conclusions

We have obtained through our numerical simulations the probability of switch as a function of the duration of the pulse, of the amplitude of pulse magnetic applied field, of the damping parameter  $\alpha$  and of the additional applied field along the easy axis.

The results of the numeric simulation show that there is not only a deterministic response of which the device switches with probability of exactly 1 or 0 [3], but, also, there is a stochastic nature of precessional switching as was obtained in experiments (see [3], Fig. 1).

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