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Micromagnetic simulations of fast switching in single-domain ferromagnetic particles

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In this paper we present the results of numerical simulations concerning the thermal effects in the dynamics and the switching probability of one spin magnetic particle with a thin-film like geometry and in-plane anisotropy. The dynamics of magnetization vector is calculated using the LLG equation and Langevin formalism. We have determined the maximum angle of dispersion due to thermal fluctuation as a function of temperature and we calculate the time window when switching has probability 1 and study this as a function of the applied field.

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1. Introduction

The precessional switching is a well established way of ultrafast switching in magnetic nanoparticles [1-4]. In this frame, short magnetic pulses are applied to a ferromagnetic sample, usually a thin film with a thickness of the order of 10 nm and the dynamics of magnetization is studied using methods like magneto-optical Kerr effect (MOKE) [5], second harmonic generation [6] or time- and spin-resolved two photon photoemission [7]. The field pulse duration has reached the sub-picosecond range.

In the simulations we take into consideration a single particle with thin-film geometry and in-plane anisotropy (Fig. 1). The switch of the magnetization is realized using a pulsed magnetic field with a rectangular shape in time, applied perpendicular to the easy axis, in the film plane. The dynamics of the magnetization vector is calculated using the stochastic Landau-Lifshitz-Gilbert equation:

$$\frac{d\vec{m}}{d\tau} = -\left[\vec{m}\times\left(\vec{h}_{eff}+\vec{h}_{th}\right)\right] - \alpha\left[\vec{m}\times\left[\vec{m}\times\left(\vec{h}_{eff}+\vec{h}_{th}\right)\right]\right] \qquad (1)$$

in which $\vec{m}$ represent the normalized magnetization ($\vec{M}_s / M_s$), $\vec{h}_{eff} = \vec{H}_{eff} / M_s$ is the normalized deterministic effective field, the thermal fluctuations are taken into account in the term $\vec{h}_{th}$ (thermal field), time is in units of $1/(\mu_0 \gamma M_s)$, M_s is the saturation magnetization, α is the damping parameter and γ is the gyromagnetic ratio. The thermal field $\vec{h}_{th}$ is considered to be a stochastic Gaussian process with the statistical properties: $\left\langle h_{th}^i \right\rangle = 0$ and $\left\langle h_{th}^i, h_{th}^j \right\rangle = 2D\delta_{ij}\delta(t)$ where $i, j \in \{x, y, z\}$ and D measures the intensity of the thermal noise. The stochastic LLG equation is integrated using the Heun algorithm which converges to the Stratonivich interpretation [8,9]. The demagnetizing factors in the thin-film element considered here are in plane equal to 0 and perpendicular to the film -1, this conducting to a demagnetizing field (H_d) on Oy axis (see Fig. 1). The deterministic effective field is the sum of the exterior magnetic field applied, the anisotropy field and the demagnetizing field:

$$\vec{h}_{eff}(\vec{m}) = h\vec{a}_1 - m_y\vec{a}_2 + Km_z\vec{a}_3 \qquad (2)$$

where $\vec{a}_1$, $\vec{a}_2$ and $\vec{a}_3$ are the unit vectors of the cartesian axes *x*, *y*, and *z*, h is the normalized field applied (see Fig. 1) and K is the anisotropy constant. In the numerical simulations we have considered values corresponding to the FePt nanoparticle with the anisotropy field H_k = 5700 kA/m, the saturation magnetization M_s = 1100 kA/m and the damping parameter α = 0.03.

2. Simulations

In order to calculate the switching probability [10] we determine first the maximum dispersion angle of the initial state as a function of temperature. Starting from small angles of the magnetization vector with respect to the easy axis we calculate the dynamics of the magnetization in zero applied field around the equilibrium position due to the thermal fluctuations for a very long time compared to the period of precession. We observe that the maximum angle of dispersion depends only on the temperature. Fig. 2 shows the dependence of the maximum angle of dispersion as a function of temperature. The angular dispersion is of 7.75 degrees at 50 K and is increasing up to 19.2 at 300 K. We define Ω as the solid angle which has a planar opening two times the maximum dispersion angle.

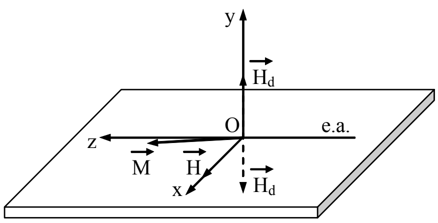


Fig. 1. Magnetic thin film subject to in-plane applied field. The easy axis is along the Oz axis.

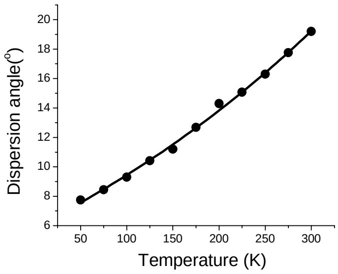


Fig. 2 The maximum dispersion angle as a function of temperature.

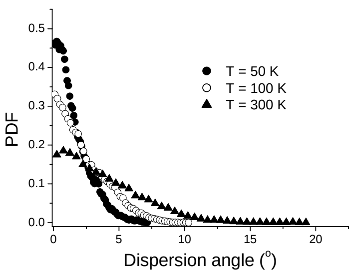


Fig. 3. PDF of the dispersion angle for three temperatures (50 K, 100 K and 300 K).

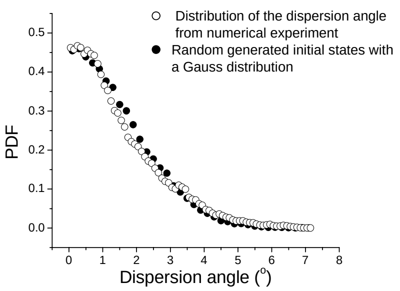


Fig. 4. PDF of the dispersion angle and for random generated initial states (T = 50 K).

This way, for a large number of events, one may obtain the probability distribution function (PDF) for the initial conditions of the magnetization. Figure 3 shows the PDF of the dispersion angle calculated for three temperatures. We have fit the PDF with an exponential decay function and with a Gauss function and we observe that the Gaussian fit is a better approximation, the correlation in this case was $R^2 = 0.9940$ and for the exponential function, $R^2 = 0.9847$. Next, we have generated a number of angles (5000) using the same Gauss distribution determined above and considered them as initial starting conditions for the calculus of the magnetization trajectory and the probability of switching [6]. In figure 4 we show the PDF of the dispersion angle from the numerical experiment due to the thermal effects and the calculated PDF for the random generated angle using the Gaussian distribution.

In fig. 5 are represented the projections of the magnetization vector tip during the applied field (~2 ns, H = H_k) calculated with the Langevin formalism (T = 50 K) and with classic LLG equation ($d\vec{m}/d\tau = -(\vec{m}\times\vec{h}_{eff}) - \alpha[\vec{m}\times(\vec{m}\times\vec{h}_{eff})]$). One may see that the trajectories of the magnetization calculated in those two modes are the same, the influence of the thermal noise being very, very small. Referring to the computing times, the classical method (LLG) is much faster and taking into consideration the above discussion, in the next results we calculate the magnetization trajectory using this method and considering a solid angle corresponding to a temperature of 50 K.

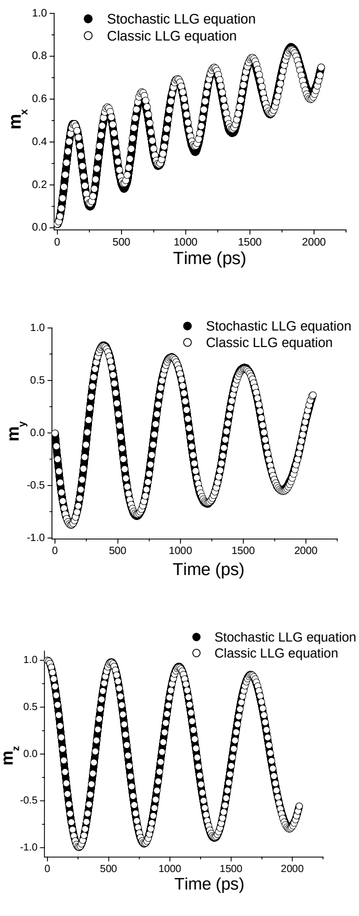


Fig. 5. The projections of the magnetization m_x (a), m_y b) and m_z (c) during the applied field ~2 ns ($H = H_k$, $T = 50$ K, $\alpha = 0.03$) calculated with the classic LLG equation and with the Langevin formalism.

In terms of the time needed to have a switch event when the pulsed magnetic field is applied, there may be defined two critical times for every precession period. The first critical time t_{c1}^{Ω} is the point of no return when, for pulse lengths exceeding this value one obtains the switch event while, for a pulse shorter than that, the magnetization comes back to the same equilibrium position, *for any value* of the initial state of orientation of the magnetization vector in a certain solid angle Ω.

At the second critical time t_{c2}^{Ω} of the precession, for a pulse length lower than this value we still obtain the switch event, while for longer pulses, the magnetization precesses back to the original state of equilibrium again *for any value* of the orientation of the magnetization vector in a certain solid angle Ω.

Fig. 6 shows the switching probability versus the duration of the field pulse. We have marked the critical times t_{c1}^{Ω} and t_{c2}^{Ω} corresponding to the first precession of the magnetic moment. The regions with probability value equal to 1 in Fig. 2 correspond to the first and respectively second precession of the magnetization. The probability of switching changes from 0 to 1 in an interval of approximately 43ps and the time window of probability 1 has 507ps in the case of first precession of the magnetization. For the case of the second precession of the magnetic moment, one needs 207 ps to reach probability 1 and the time interval of probability 1 is 448 ps.

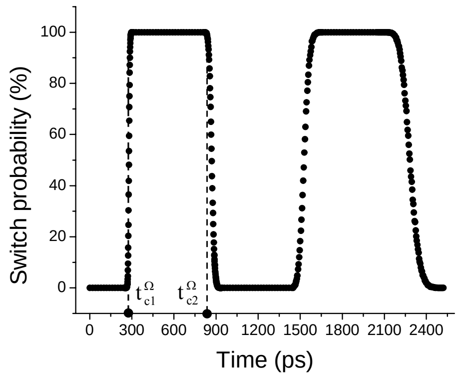
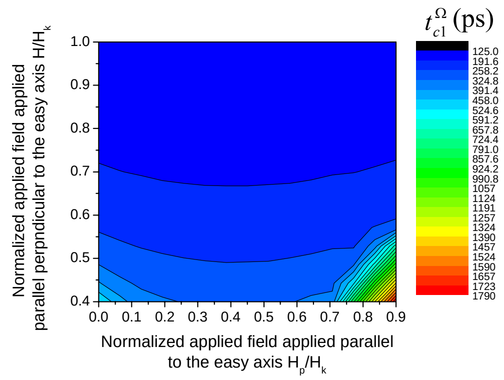
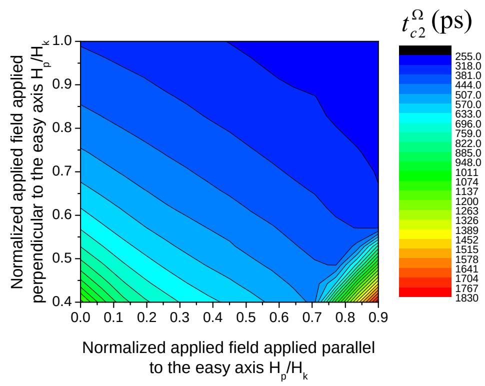


Fig. 6. Switching probability as a function of the duration of the field pulse ($H = 0.5\ H_k$).

In order to find the lowest possible time that provides switching probability 1 one may consider the possibility of applying the magnetic pulse within a certain angle with respect to the easy axis of the particle. This is equivalent to applying two magnetic fields, one perpendicular to the easy axis (H) and one parallel to it (H_p) but in the direction opposite to the direction of the initial direction of the magnetization. In Fig. 7 (a) and (b) are represented the maps of the minimum time (t_{c1}^{Ω}), respectively the maximum time (t_{c2}^{Ω}) to reach the certain switch as a function of the magnetic fields applied perpendicular and parallel with the easy axis. For smaller value of magnetic field applied (H) perpendicular to the easy axis, in order to obtain best minimum times for magnetization switching, the parallel field applied (H_p) has an important role, but also if the value of H_p becomes greater, then t_{c1}^{Ω} starts to increase. For greater value of perpendicular field applied, the minimum time depends almost exclusively on this field, the variation of t_{c1}^{Ω} as a function of the parallel field applied being very small. From energetic point of view, we may see it is more convenient to apply just a magnetic field (H) perpendicular to the easy axis.



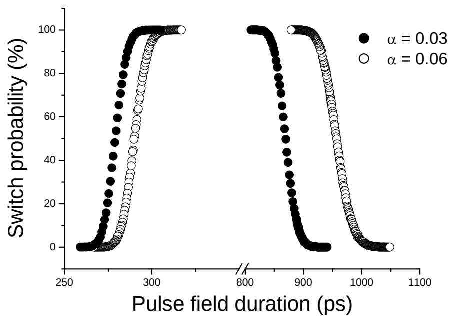
a



b

Fig. 7. Minimum time (a) and maximum time (b) of the certain switch as a function of the magnetic fields applied perpendicular (H) and parallel (H_p) with the easy axis.

We have also analyzed the dependence of the switch probability on the damping parameter and on the shape of the sample. From Fig. 8 (a) one may observe that, for α smaller, we obtain the certain switch in a shorter time. This can be explained by the fact that if α is smaller, right hand side term in the LLG equation, which describes the precessional motion, becomes more important than the damping term, so, the magnetization precession becomes more faster.



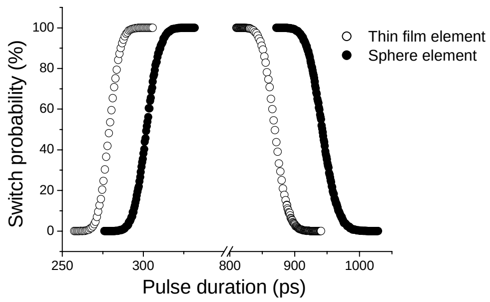


Fig. 8 Probability of switching vs. pulse field duration as a function of the damping parameter α – (a) and as a function of the shape of the sample – (b). The amplitude of the applied field is 0.5 H_k.

The demagnetizing field which appears during the applied field has an important role in the dynamic of the magnetization and we studied the effect of this field in the switching probability by considering first a nanoparticle with a thin-film like geometry and next a nanoparticle with a spherical shape and the same volume. We calculate the demagnetizing field in those two cases and we found for thin film H_d = 650.1 kA/m and for sphere H_d = 366.6 kA/m. In Fig. 8 (b) one may see that, for a thin film, the probability of switching starts to increase and reaches the value 1 in a shorter time than for the spherical nanoparticle (due to a bigger demagnetizing field). The time window of switch probability 1 for thin film is 507 ps and for spherical shape is 546 ps.

3. Conclusions

We evaluated the dispersion angle, in zero applied field, due to thermal fluctuations and we calculated the probability distribution function of the dispersion angle for different temperatures. We calculated the probability of switch as a function of the duration of the magnetic field pulse and obtained the critical times corresponding to the first period of precession of the magnetic moment, which defines the switching probability 1 time window. In order to find the minimum time to obtain a certain magnetization switch we have obtained a map of the critical times as a function of the amplitude and direction of the magnetic field applied. We studied the dependence of the switch probability as a function of the damping parameter and the shape of the ferromagnetic nanoparticles.

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