Influence of the size of uniaxial magnetic nanoparticle on the reliability of high-speed switching

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The effect of thermal noise at 300 K on the reversal of a single-domain uniaxial magnetic nanoparticle is studied on the basis of computer simulation of the Landau-Lifshits equation. It is demonstrated that the decrease in the particle size can lead to the increase in the mean reversal time up to two times due to the noise delayed switching effect. This negative effect can be suppressed by the proper choice of the angle between the reversal magnetic field and the anisotropy axis. The minimal volume of a nanoparticle that provides the reliable process of switching, is found for certain values of the reversal magnetic field angles. It is demonstrated that the sensible choice of the reversal magnetic field angle allows to use much smaller particles without degradation of the switching reliability.

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The decrease in sizes of magnetic nanoparticles used in storage media leads to the increase in fluctuations and, therefore, to increase in storage and switching errors. At finite temperature, the most crucial problem is the stable magnetic reversal: the remagnetization process must occur with minimal switching time and the standard deviation. Due to small size, the nanoparticles can often be considered as single-domain particles[1–4] since the inhomogeneous distribution of the magnetization is energetically disadvantageous. Theoretical investigation of noise-assisted high-speed switching of magnetization vector is of crucial importance both for magnetic recording media[5] and magnetoresistive memory.[2–4] Due to the complexity of the model, described by the time-dependent Landau-Lifshits equation with noise,[6] starting from the seminal paper[7] mostly the relaxation times of magnetization in the case of static magnetic field have been studied.[8–11] References 12 and 13 were focused on the effect of noise and high-frequency rotating magnetic field on the magnetic dipole dynamics. However, the practically interesting effect of fluctuations on the high-speed switching of magnetic single-domain particles has been investigated only recently.[14] In Ref. 14, it has been demonstrated that, in a certain range of parameters, with increase in the working temperature the mean reversal time (MRT) of the particle increases. This is known as the noise delayed switching (NDS) effect,[15] and can lead to significant degradation of magnetic recording media. However, to our knowledge, the effect of decreasing the size of magnetic nanoparticles at room temperature, which will eventually lead to the same negative effect of increase both the switching errors and the switching time, has not been studied in the literature.

In the present Brief Report, the investigation of the reversal process of a single-domain uniaxial magnetic particle by a pulse signal has been performed on the basis of computer simulation of the Landau-Lifshits equation with thermal fluctuations taken into account. It is known that if there is a deterministic trajectory, perturbed by a small noise (as it is, e.g., when the system is switched from one state to another one by a strong external signal), the corresponding probability density is close to the Gaussian one, which is traveling along the trajectory and expanding due to diffusion. The same quasi-Gaussian distribution will be for the first passage times (FPT) of a certain boundary. In this case, the ratio of standard deviation to the mean value of FPT is a good estimate of the reliability of the system. As it follows from the analysis of Ref. 14, if this value is equal to 0.1, the probability of nonswitching is on the order of 10^{-23}, which is enough for most of practical applications. The present Brief Report is devoted to studying the behavior of particles with different volumes and is aimed to find a minimal size of a particle for which the reversal is still reliable.

The dynamics of the magnetic dipole is described by the Landau-Lifshits equation,

$$\frac{d\vec{M}}{dt} = -\frac{\gamma}{\beta}[\vec{M}\times\vec{H}] - \frac{\alpha\gamma}{\beta M_s}[\vec{M}\times(\vec{M}\times\vec{H})], \qquad (1)$$

where $\vec{M}$ is the magnetization of a particle, $M_s=|\vec{M}|$—saturation magnetization, γ—gyromagnetic constant, α—damping constant, $\beta=1+\alpha^2$, $\vec{H}$—full magnetic field. The magnetization $\vec{M}$ is characterized by its direction, M_s is a constant, and depends on the material only. The magnetic field $\vec{H}$ includes all components affecting the particle such as anisotropy field, fluctuational field, and external field: $\vec{H}=\vec{H}_a+\vec{H}_e+\vec{H}_T$. Anisotropy field has the form $\vec{H}_a=\frac{2K}{M_s^2}(\vec{M},\vec{n})\vec{n}$. It is caused by the chosen direction that is easier for dipole to be oriented along since it gives an additional energy $W_a=-\frac{KV}{M_s^2}(\vec{M},\vec{n})^2$—the so-called “light axis” anisotropy, here $\vec{n}$ is the normalized vector collinear to this axis, K is the anisotropy constant, and V is the volume of the particle. Fluctuational field $\vec{H}_T$ is assumed to be white Gaussian noise with zero mean and intensity $\frac{2\alpha kT}{\gamma M_s V}$,[14] where k is the Boltzmann constant and T is the temperature. The external field is the instrument for switching the nanoparticle, and our aim is to optimize its parameters to maximize the switching reliability.

Let us specify the subject of our investigation. We consider a single magnetic dipole with anisotropy supposed to be in z axis. The dipole is switched from one equilibrium state $(0,0,+M_s)$ to the other one $(0,0,-M_s)$. The external field is taken as sinusoidal pulse: $H_e=H_0\sin(\pi t/t_p)$ (see the

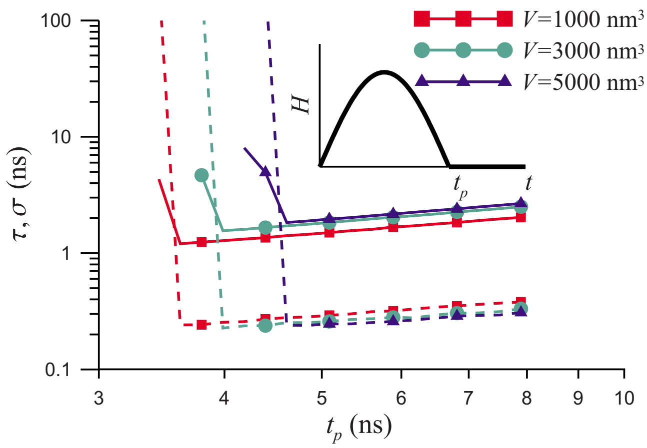

FIG. 1. (Color online) MRT (solid curves) and SD (dashed curves) versus pulse duration for particles of different volume for $\theta=0$. Inset: the shape of the switching pulse.

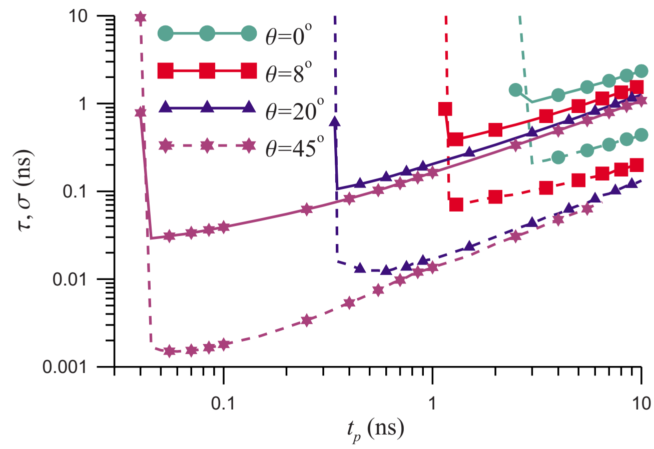

FIG. 2. (Color online) MRT (solid curves) and SD (dashed curves) versus pulse duration for the particle with $V=1000$ nm^3 and different angles θ.

inset of Fig. 1). We study the behavior of the system at room temperature ($T=300$ K) so the influence of noise cannot be neglected. Due to noise the particle is fluctuating near its equilibrium state when there is no external signal. We consider the first passage of a certain boundary as the switching of the dipole into another state. The XY plane is taken as this boundary ($z=0$). Since the process is stochastic, we will calculate its statistical characteristics in the sequence of N realizations. The first is the mean reversal time (MRT, τ): $\tau=\langle t\rangle=\Sigma_{i=1}^{N}t_i/N$ where t_i is the random first passage time of every realization. The second is the standard deviation (SD, σ): $\sigma=\sqrt{\langle t^2\rangle-\langle t\rangle^2}$. The switching is considered to be reliable enough when $\sigma\ll\tau$. Our research is based on computer simulation of Landau-Lifshits equation using Heun scheme. We will use the following parameters: $\alpha=0.1$, $\gamma=1.76\times10^7$ Hz/Oe, $M_s=360$ emu/cm^3, $K=7.2\times10^5$ erg/cm^3. In this case the coercivity $H_c=2K/M_s=4000$ Oe (maximum of the anisotropy field). Obviously, the amplitude of the switching pulse should be larger than H_c, here it is taken to be $H_0=6000$ Oe. We will study how MRT and SD depend on the pulse width t_p, the volume V, and the angle θ between external field and z axis. The temperature is taken to be 300 K, and the considered values of V vary from 10 nm^3 to 100 000 nm^3. Our main purpose is to find the area of the parameters (especially volume of the particle), where the switching is the fastest and the most reliable.

First, let us consider the simplest case, where the switching is performed with sinusoidal field, collinear to z axis. If $T=0$, there is no noise effect in the system, and the dipole will stay in its equilibrium state for an infinitely long time, though this state is unstable. However, at $T=300$ K thermal fluctuations help to turn the particle into another state. The plots of τ and σ as functions of pulse duration are presented in Fig. 1. It is seen that these functions have minima, see Ref. 14. The decrease in the MRT at large t_p is due to the fact that with decrease in the pulse width the potential barrier disappears faster. With further shortening of the pulse, the magnetization does not have enough time for the complete reversal during t_p, so the MRT increases. This, actually, means that for rather short pulses the transition occurs due to effect of fluctuations (the so-called noise-induced switching). It is important to mention that for the plots, presented in Fig. 1, the bigger is the particle, the longer is the most optimal pulse. The minimum of MRT is higher for larger dipoles: noise influence becomes less essential, so it is more difficult for the particle to be moved from the initial unstable state. However, the switching is more reliable for larger particles, the ratio σ/τ decreases.

Now let us vary the direction of external field for the same particle. We will find that the MRT can be reduced in about ten times without loosing the quality of switching by choosing another angle θ between external field and z axis (Fig. 2). It has already been shown that the best angle is about 45°.[5,14,16] Let us note that MRT and SD reach their minima at slightly different points.

Another interesting effect can be found in this system when θ is not zero. Let us fix $\theta=5°$ and change the volume of the dipole. We will see that, with decrease in V, MRT and SD minima are increasing (Fig. 3). It seems to be unusual, especially if we remember our first case (Fig. 1). Here larger

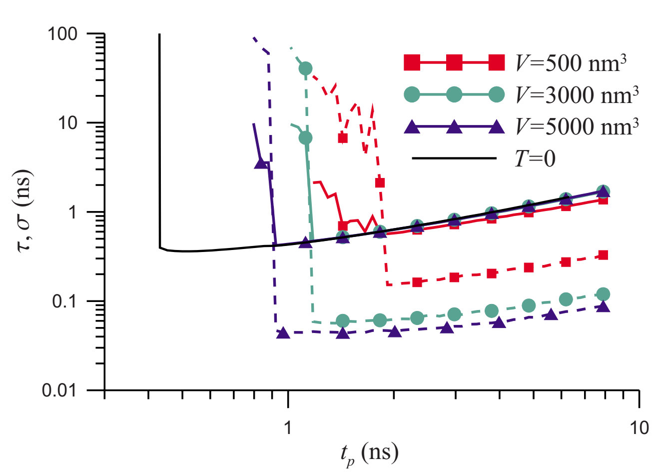

FIG. 3. (Color online) MRT (solid curves) and SD (dashed curves) versus the pulse duration for the particles with different volumes when $\theta=5°$. Black solid curve—$T=0$.

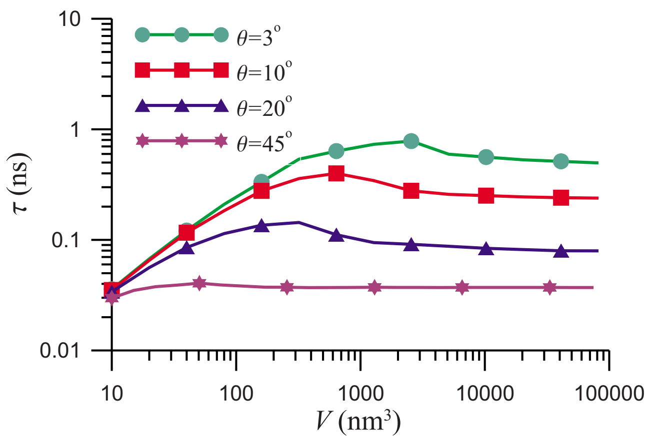

FIG. 4. (Color online) Minimal MRT versus volume V for different θ.

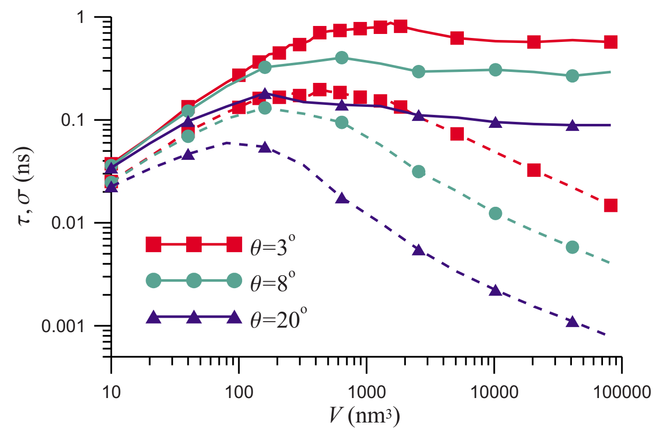

FIG. 5. (Color online) Minimal SD (dashed curves) and the corresponding MRT (solid curves) versus volume V for different angles θ.

dipoles can be switched not only more reliably but also faster. This is a manifestation of the noise delayed switching effect.[15] When the particle is in the unstable equilibrium state ($\theta=0$), all directions of the switching are equal. Another situation takes place if there is a nonzero angle. This helps the dipole to be switched into the one direction (e.g., clockwise) even without noise, and protects from switching into the opposite direction (e.g., counterclockwise), creating a potential barrier. However, due to the noise, the dipole can also be turned into the nonpreferred direction, so the switching takes more time. The contribution of such switching into the opposite direction becomes more pronounced with the volume decrease.

Let us study the behavior of the minimum of MRT as the function of the volume for different angles. The results are presented in Fig. 4. We can see that every curve (apart from $\theta=0$) has an interval of increasing, then reaches its maximum, after which it decreases, tending to a constant, that is the reversal time in the limit $T\to 0$. Here the NDS effect is very pronounced: with decrease in the particle size not only the SD can increase dramatically, but also the MRT can increase up to a factor of 2. The NDS effect corresponds to the interval of decreasing of the curve. It is seen that the magnitude of this effect depends on the direction of the external field. It is maximal for small angles $\theta=3°-8°$ and negligibly weak for large angles (curve for $\theta=45°$). As for little particles $V\approx 10\ \text{nm}^3$, their MRT practically does not depend on θ because here the noise for the chosen parameters is much stronger than the external pulse, and is the dominant mechanism of switching. It is also seen that the maximum of the curve moves to the area of larger particles, when θ becomes smaller. We have already mentioned that MRT and SD minima correspond to different pulse widths, so if we take the minimal MRT, the SD at the same value of the pulse duration t_p can be too large that destroys the reliable switching. That is why it is also important to study the minimum of SD as the function of volume and to calculate MRT at the points of SD minima, see Fig. 5. As it follows from Fig. 5, the increasing of θ leads to decreasing of SD. As for MRT, it does not depend significantly on V for big enough particles.

To find the area of reliable switching, we examine how the relation SD to MRT σ/τ depends on the volume for different angles between the external field and the anisotropy axis (Fig. 6). We consider this coefficient to be appropriate for practical applications when it is smaller than 0.1, see below. Taking this into account we can conclude that the angle $\theta=3°$ allows us to use particles with V larger than 8000 nm^3, for $\theta=5°$ particles larger than 3000 nm^3 are acceptable, but if we choose $\theta=45°$, the volume can be decreased to 200 nm^3. So, the difference may be up to 40 times, and the increase in the resulting magnetic recording density can be dramatic.

In certain cases the distributions of the first passage times can be very far from Gaussian, e.g., when the noise-induced transitions occur over high potential barriers[17] and the use of just two first cumulants (the mean and the variance) to describe the switching process can be not enough. To check that the MRT and SD give an adequate description of the high-speed switching of magnetic single-domain particles, we have calculated the probability densities $w(t)$ of the first passage times for various parameters, see Fig. 7. All curves for $\theta=5°$ except one, marked as NDS, are calculated for $t_p=4$ ns, and curves for $\theta=45°$—for $t_p=1$ ns. If $\sigma/\tau<0.1$, the curves are perfectly fit by the Gaussian distribution $w(t)=\exp\{-(t-\tau)^2/2\sigma^2\}/\sqrt{2\pi\sigma^2}$. Namely, due to this fact the

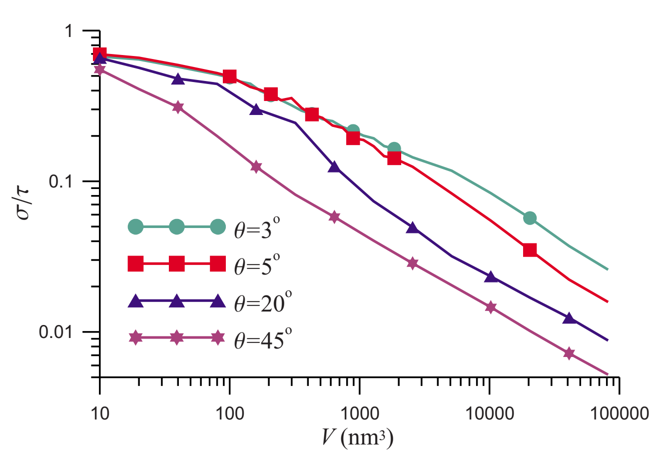

FIG. 6. (Color online) The ratio SD/MRT taken at the point of minimal SD versus volume V for different angles θ.

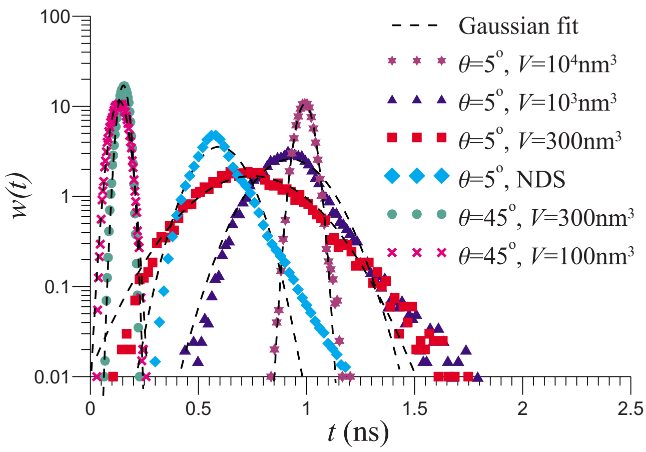

FIG. 7. (Color online) The probability density of first passage times for various parameters (symbols) and Gaussian fit (dashed curves).

boundary of the reliable switching $\sigma/\tau<0.1$ is chosen, which gives the nonswitching probability of the order of 10^{-23}, because even if the lower distribution tails are strongly non-Gaussian and very steep, they will not seriously affect the nonswitching probability. With increase in noise intensity (decrease in the volume), the switching becomes more noise induced and the distribution starts to deviate from the Gaussian one, see curves for $\theta=5°$ and $V=1000$ nm^3, $V=300$ nm^3, where the switching is not reliable enough for practical applications, see Fig. 6. The largest deviation from the Gaussian distribution has been observed in the case of maximal NDS effect ($\theta=5°$, $V=1000$ nm^3, $t_p=2$ ns), however, even in this case the calculated MRT value $\tau=0.596$ is close to the maximum of the probability distribution $t_{max}=0.57$.

In the present Brief Report, we have investigated statistical characteristics of switching of magnetic nanoparticles of different sizes: the mean reversal time and the standard deviation. We have found how the MRT and SD depend on the size of the particle for different external field directions at room temperature. It has been shown that, choosing this direction properly, one can significantly decrease both MRT and SD. Then, we have indicated the area of parameters, where the noise delayed switching effect is observed. It is demonstrated that this effect strongly depends on the chosen direction of the applied magnetic field, and the switching time is maximal for a certain size of a particle. Finally, we have found the minimal volume of a nanoparticle that provides the reliable process of switching, and demonstrated that the sensible choice of the angle θ allows to use much smaller particles without degradation of switching reliability. This result is of real practical importance, especially as far as increasing of magnetic recording density is concerned.

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