Effect of noise on the high-speed reversal of single-domain uniaxial magnetic nanoparticles

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The effect of noise on the reversal of a single-domain uniaxial magnetic nanoparticle is studied on the basis of computer simulation of the Landau-Lifshits equation. The interplay between resonant activationlike and noise-delayed switching effects is investigated. Namely, it is demonstrated that for the dipole reversal by the pulse with smooth fronts, there exists the optimal pulse width, which minimizes the mean reversal time (MRT) and the standard deviation (SD). Both the MRT and the SD significantly depend on the angle between the reversal magnetic field and the anisotropy axis. In comparison with the uniaxial symmetry case at the optimal angle $\theta=45°$, the MRT can be decreased from a factor of seven up to two orders of magnitude, and the jitter can be decreased from one to three orders of magnitude for damping α ranging from 1 to 0.01. It is demonstrated that for $\theta=5°$ the increase in temperature from 4 to 300 K leads to doubling the MRT due to the noise-delayed switching effect.

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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 (jitter). 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 the magnetization vector is of crucial importance both for magnetic recording media[5] and for magnetoresistive memory.[2–4] During the past decades, in nonlinear systems driven by noise, the nontrivial phenomena such as resonant activation (RA),[6] stochastic resonance,[7] and noise-delayed switching (NDS) (Ref. 8) have been observed. In magnetic systems, however, the existence of only stochastic resonance effect has been confirmed.[9] Due to the complexity of the model, described by the time-dependent Landau-Lifshits equation with noise,[10] mostly the relaxation times of magnetization have been studied.[11–14] Without account of noise it has been found before that there is an optimal angle between the applied magnetic field and the anisotropy axis, which is typically around 45°;[5,15] with the decrease in the magnetic-field rise time, the coercivity of the magnetic particle (dynamic coercivity) increases.[16,17] In Refs. 3 and 4 the optimization of the pulse duration of the switching field has been performed to suppress ringing. At finite temperature the most crucial problem is the stable magnetic reversal—the remagnetization process must occur with minimal switching time and standard deviation. It is very important for applications in storage media to investigate the RA-like effects and NDS effects since their proper utilization can significantly improve the performance of magnetic recording devices. These effects may play positive and negative roles in the accumulation of fluctuational errors in recording media—the RA-like phenomenon minimizes timing errors, while the NDS phenomenon increases the reversal time. The interplay between RA-like and NDS effects has been studied in different nonlinear models from Josephson junctions[18] to neural systems.[19] However, the dynamics of the magnetization is much more complex and essentially three dimensional, which must lead to specific peculiarities. The mean reversal time (MRT) of magnetic particles was studied in Refs. 20 and 21 and in Ref. 21 it was shown that during noise-assisted reversal, the noise leads not to the increase but to the decrease in MRT.

In the present Brief Report the investigation of the reversal process of a single-domain uniaxial magnetic particle has been performed on the basis of computer simulation of the Landau-Lifshits equation with thermal fluctuations taken into account. It is focused on the investigation of resonant activationlike and noise-delayed switching phenomena with the aim of finding an optimal regime of reversal with the smallest mean reversal time and standard deviation.

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, $\vec{H}$ is the effective magnetic field, γ is the gyromagnetic constant, $\beta=1+\alpha^2$, α is the damping, and $M_s=|\vec{M}|$ is the saturation magnetization. The effective magnetic field contains the following components: $\vec{H}=\vec{H}_a+\vec{H}_e+\vec{H}_T$, where $\vec{H}_a$ is the anisotropy field, $\vec{H}_e$ is the external field, and $\vec{H}_T$ is the fluctuational field. The fluctuational field is assumed to be white Gaussian noise with zero mean and the correlation function $\langle H(t)_T H(t')_T\rangle = \frac{2\alpha kT}{\gamma M_s V}\delta(t-t')$, where k is the Boltzmann constant, T is the temperature, and V is the volume of the magnetic particle.

Let us consider the reversal of the magnetic dipole initially magnetized along the anisotropy axis and along the x axis from the state $\vec{M}[+M_s,0,0]$ to the state $\vec{M}[-M_s,0,0]$. To find the area of parameters where the fastest and most reliable reversal occurs, as the characteristic to be studied let us choose the first passage time of a certain boundary. The mean first passage time (the MRT) τ and the standard deviation of the first passage time σ (SD, jitter) are[22] $\tau=\langle t\rangle = \Sigma_{i=1}^N t_i/N$, $\langle t^2\rangle = \Sigma_{i=1}^N t_i^2/N$, and $\sigma=\sqrt{\langle t^2\rangle - \langle t\rangle^2}$, where t_i is the first passage time of an absorbing boundary and $N\geq 10\,000$ is the number of realizations. As in Ref. 23 let us choose the

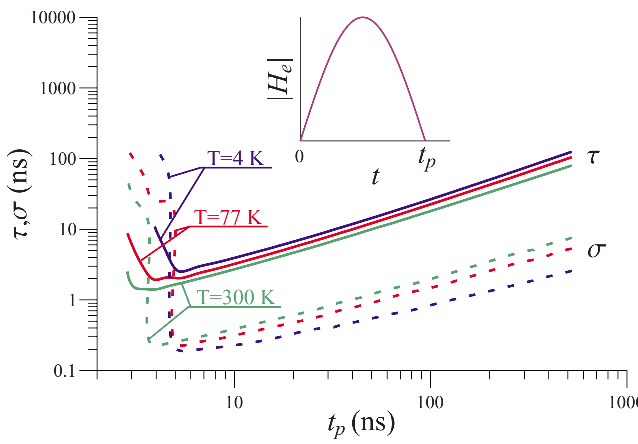

FIG. 1. (Color online) The mean reversal time (solid curves) and the standard deviation (dashed curves) versus pulse width for the zero angle between the anisotropy axis and the driving field $\theta=0°$. Inset: The driving pulse.

boundary as the passage of the point $\vec{M}[0,M_y,M_z]$.

In the calculations it is convenient to use the parameters related to the magnetic recording media:[5] $\alpha=0.1$, $\gamma=1.76 \times 10^7$ Hz/Oe, $M_s=360$ Oe, $V=2\times 10^3$ nm^3, and the anisotropy constant $K=7.2\times 10^5$ erg/cm^3. The static coercivity is $H_c=2K/M_s=4000$ Oe. For modeling we take the amplitude of the magnetic field to be $H_0=6000$ Oe. It is known that the driving by the signal with sharp fronts leads to the minimal MRT.[18] However, the pulses used in real recording media systems have finite rise time.[2–5] As an example of a driving with smooth fronts, similar to those in the experiments,[2–5] we consider the sinusoidal pulse $\vec{H}_e=\vec{e}H_0 \sin \pi t/t_p$ with the width t_p (see the inset of Fig. 1), where $\vec{e}$ is the unitary vector of the magnetic-field direction. The considered range of temperatures from 4 to 300 K for the above listed parameters obviously leads to the noise intensity, which is much smaller than the activation energy of the system, so the reversal under the magnetic pulse field can occur even without noise for the angles between the anisotropy axis and the driving field, appreciably different from zero. If the switching during t_p does not happen, the computation is continued for $\vec{H}_e=0$ until some long period of time t_f much larger than any other relaxation-time scale. Our aim is to find the parameter range, for which the reversal by a smooth pulse takes place quickly and reliably.

The Landau-Lifshits equation with noise has been computed both by the Heun method programmed in FORTRAN and by the specialized package SIMMAG (simulation of micromagnets), developed in the laboratory of mathematical modeling of the Institute for Physics of Microstructures of RAS.

It is known that for zero temperature $T=0$ the reversal of the dipole by the longitudinal field, $\theta=0°$, does not occur since the dipole is in the equilibrium state, even if this state is unstable. The presence of thermal fluctuations allows to move the particle away from this equilibrium state. In Fig. 1 the plots of the mean reversal time τ and the standard deviation σ are presented. First of all, it is seen that both τ and σ have minima as functions of the driving pulse width. This resembles the resonant activation phenomenon[6] and indicates that both these temporal characteristics can be minimized by the optimal choice of pulse duration. A similar effect of noise suppression by strong external driving has recently been observed for Josephson junctions[18] and neural systems.[19] The decrease in the MRT at large durations is due to the fact that with a decrease in the 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 the effect of fluctuations (the so-called noise-induced switching). The standard deviation with decrease in the pulse width behaves similarly to τ, but the curves for different temperatures cross each other. For long pulses, smaller temperature leads to smaller σ; but for short pulses, vice versa. This is also explained by the transition from the regime of switching by the external field to the noise-induced escapes since it is well known (see, e.g., Ref. 22) that in the noise-induced regime the SD is approximately equal to the MRT.

Let us point out a few more features, which are clearly visible in Fig. 1; higher temperature leads to smaller MRT, i.e., noise allows us to speed up the reversal, which agrees with the predictions of Ref. 21 but contradicts the results of Ref. 18. Besides, the dependence $\sigma \sim \sqrt{T}$ (usual for Josephson junctions at large pulse widths) is not also reproduced here. From Fig. 1 one can see that $\sigma(T)$ dependence is slower than $\sqrt{T}$. The explanation of such an unusual behavior is the specific nature of the reversal process at $\theta=0°$; in difference with the Josephson junctions,[18] due to the location of initial conditions at the unstable equilibrium point, the reversal is impossible at zero temperature and the deterministic reversal trajectory does not exist. That is why fluctuations help to leave the unstable initial state and, namely, this leads to the described above peculiarities. It should be noted that the above investigated case ($\theta=0°$, which is mostly studied analytically)[11–13] is degenerate. First, technically the angle between the anisotropy axis and the external field can be set up with a certain precision and second, the MRT is largest in this case (see below).

In Fig. 2 the MRT and SD are given for three different values of angles $\theta=0°$, 5°, and 45° for $T=300$ K and three different temperatures for $\theta=5°$. First, let us focus on the curves for $\theta=5°$. While at large t_p one can see little decrease of MRT with increase of the temperature, at small t_p around minimum the opposite effect of noise-delayed switching is clearly visible, which is quite similar to the one observed before for Josephson junctions[18] and—in the general case—for nonlinear systems.[8] Notice that for the considered value of $\theta=5°$ the MRT increases about two times for the temperatures from 4 to 300 K. Besides, here the SD behaves as $\sigma \sim \sqrt{T}$ (see Ref. 18).

From Fig. 2 it is obvious that for $\theta=45°$ the reversal is faster and more stable than for $\theta=0°$ and 5° at all other equal conditions. Besides, the difference between MRT for the angles $\theta=0°$ and $\theta=5°$ is two times, while the difference of SD is about three times. For the cases $\theta=5°$ and $\theta=45°$ the gain is even larger, more than one order for MRT and almost two orders for SD. This means that the reversal process principally depends on the precession of the magnetic dipole and

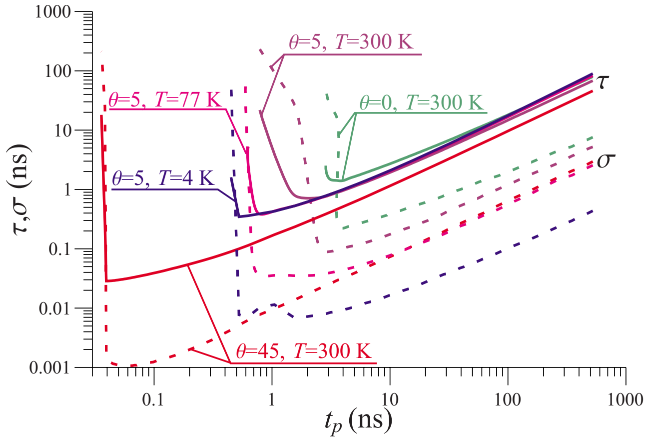

FIG. 2. (Color online) The MRT (solid curves) and SD (dashed curves) versus pulse width for different angles between the anisotropy axis and external field and different temperatures for $\theta=5°$.

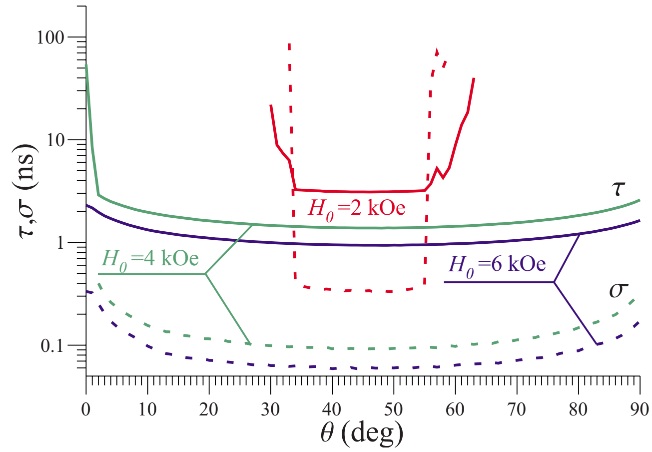

FIG. 4. (Color online) The MRT (solid curves) and SD (dashed curves) versus the angle between the anisotropy axis and external magnetic field for different values of magnetic-field amplitude ($t_p=8$ ns and temperature $T=300$ K).

it cannot be described by a simple two-state model. This result gives the quantitative substantiation for the idea to use the tilted magnetic field to speed up the reversal process[24] and also to use additional weak perpendicular magnetic field for the same purpose,[25] which actually leads to the tilt of the aggregate magnetic field. To roughly estimate the probability of nonswitching of a particle by one pulse with the duration t_p, the probability density of switching times can be considered as Gaussian with the mean τ and SD σ. Then the probability of nonswitching is $p=\frac{1}{2}\mathrm{erfc}\,((t_p-\tau)/\sqrt{2}\sigma))$. For $T=300$ K at the minimum of σ we get $p=10^{-48}$ even for $\theta=0°$. However, for $\theta=0°$ and 5° at the minimum of τ we get unacceptably large probability of 0.001 ($p=10^{-56}$ for $\theta=45°$). Therefore, namely, the minimum of SD must be chosen to provide fastest reversal with minimal noise-induced errors.

In Fig. 3 the MRT and SD are presented versus the angle between the anisotropy axis and external magnetic field θ for different values of damping α ($t_p=8$ ns and $T=300$ K). For $\theta\to 0^{\circ}$, smaller values of damping lead to larger values of both τ and σ as they must (large values of τ and σ for $\theta\to 0^{\circ}$ and $\alpha=0.01$ mean that in this range of parameters, the noise-induced reversal occurs). For larger angles, however, the MRT nearly coincide, while the SD is smaller for smaller values of α. To understand why it is so, let us plot the trajectories of the magnetization for $\theta=0°$, 5°, and 45° (see the inset of Fig. 3 for $\alpha=0.1$ and $t_p=16$ ns). One can see that the precession is largest for $\theta=0°$. For $\theta=5°$ the number of turns is smaller and for $\theta=45°$ the crossing of the boundary $\vec{M}[0,M_y,M_z]$ occurs even without precession. This explains why the reversal in the latter case happens much faster than for $\theta=0°$ and has little dependence on α in the limit $\alpha \ll 1$ (see Fig. 3). Since the length of the path is nearly the same for different α (the MRT nearly coincide) and the noise intensity is proportional to the damping, this obviously leads to smaller SD for smaller α.

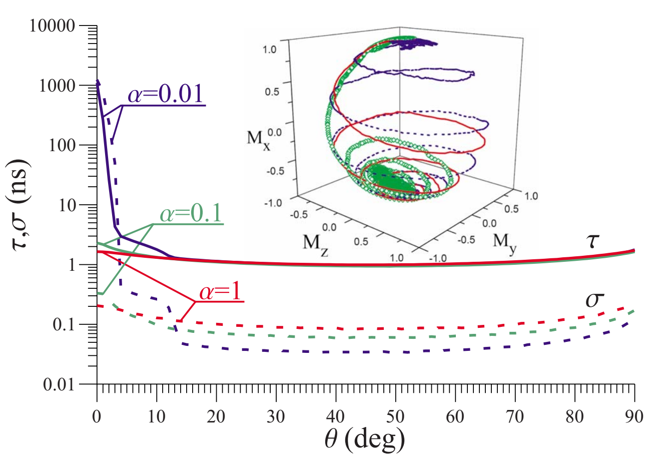

FIG. 3. (Color online) The MRT (solid curves) and SD (dashed curves) versus the angle between the anisotropy axis and external magnetic field for different values of damping α ($t_p=8$ ns and temperature $T=300$ K). Inset: Trajectories of the magnetization for different angles; $\alpha=0.1$, $t_p=16$ ns, and $T=300$ K; $\theta=0°$ (dotted curve), $\theta=5°$ (solid curve), and $\theta=45°$ (empty diamonds).

In Fig. 4 the MRT and SD versus angle θ are presented for different values of the external magnetic-field amplitude. It is seen that starting from the values 20°–30° and up to ~70°, there are flat minima of MRT and SD that correspond to the range of angles where the fastest and the most reliable reversals are realized. For the temperature $T=300$ K the reversal occurs even up to the amplitude value $H_0=2$ kOe, which is well below the static coercive field H_c, and this is with acceptably low SD. However, in the latter case the working range of angles θ is restricted by 35°–55° only (compare with the results of Refs. 15 and 23). In Ref. 1 it was suggested to use the sum of dc and small ac magnetic fields to decrease the switching field amplitude by means of nonlinear resonance. However, in such a case the switching time increases while the reliability decreases. The use of the driving at $\theta=45°$ allows us to significantly reduce the driving field amplitude without serious reduction in the thermal stability.

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Landau-Lifshits equation. The interplay between resonant activationlike and noise-delayed switching phenomena has been investigated. Namely, it is demonstrated that for the dipole reversal by the pulse with smooth fronts, there exists the optimal pulse width, which minimizes the MRT and the SD (jitter). Also, both the MRT and the jitter significantly depend on the angle between the reversal magnetic field and the anisotropy axis. In comparison with the uniaxial symmetry case, at the optimal angle $\theta=45°$ the MRT can be decreased from a factor of seven up to two orders of magnitude and the jitter can be decreased from one to three orders of magnitude for damping α ranging from 1 to 0.01. For optimal angles the SD decreases with decrease in the damping while the MRT remains nearly constant. This latter result is of crucial importance due to recent experimental evidence of the damping values even smaller than 0.01 in microstructured thin-film devices.[26] It has been demonstrated that fluctuations not only can decrease the reversal time, as it has been known for the magnetic systems and is correct for small angles θ only, but also they can significantly increase the reversal time.

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