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EDGE PINNING EFFECTS AND GIANT THERMAL INSTABILITY OF MAGNETIZATION HYSTERESIS LOOPS IN THIN NANO-SCALE MAGNETS

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Magnetization reversal modes of super-thin nano-scale particles with a high magnetization and low anisotropy are analyzed by solving magnetic moment motion equations. A new kind of thermal hysteresis instability connected with the random mutual transformation of the main magnetization modes is predicted by simulations.

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1. Introduction

Magnetization processes in bulk tiny magnets were investigated rather in detail [1], super-thing particles, however, need a special investigation. First, the tendency of magnetization alignment along the opposite particle sides creates different rest magnetization configurations and corresponding different modes of the magnetization reversal [2]. The delay of magnetization reversal by lateral particle sides leads to the additional Barkhausen switching steps on the magnetization hysteresis loop for some magnetic parameters and particle sizes. Second, the thermal fluctuations have become important for the switching processes in super-thin particles [3].

2. Method of investigations and main assumptions

To investigate some features of these effects we have used numerical simulations by solving the Landau–Lifshitz–Gilbert equation. Numerical solving methods of magnetodynamics equations are described in a row of papers (see e.g. the review [1]). We use the scheme close to that of the paper [4], which makes possible to get both fast and adequate stationary and dynamic magnetization distributions over a simulated hysteresis loop.

A super-thing magnetic particle has the thickness d less than the exchange length $\sqrt{A}/M$ ($d < \sqrt{A}/M$), where A is the exchange parameter and M is the magnetization. In this case, the magnetization may be considered uniform through the thickness.

We shall analyze the magnetization processes for the permalloy film with the magnetization $M = 800$ emu/cm^2, exchange parameter $A = 10^{-6}$ erg/ccm, and uniaxial anisotropy $K = 1000$ erg/ccm, the easy direction of which is along the particle.

To understand the thermal fluctuations influence on the switching fields, we use the dynamic approach in the analogy to the paper [3]. One should consider for this approach that there is a generated accidental uniform magnetic field $\boldsymbol{H}_i^{\mathrm{fl}}(t)$, where t is the time, in each i-th elementary grid mesh of an appropriately divided particle. This random field corresponds to the white noise characterized by the correlation function defined in accordance with the fluctuation–dissipation theorem by the standard way.

3. Rest configurations and magnetization hysteresis

Two kinds of magnetization configurations predicted in Ref. [2] for the remanent state of a super-thing rectangle particle are characterized by parallel (S-like distribution) or anti-parallel (C-like distribution) magnetizations alignment at opposite poles of the particle as shown schematically in the inset of Fig. 1.

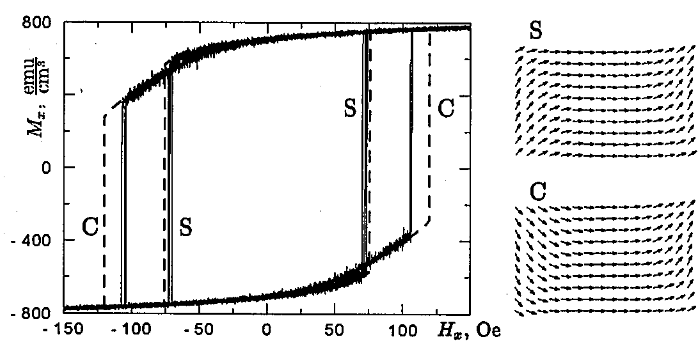

Fig. 1. Magnetization hysteresis loops for the main magnetization reversal modes (S- and C-type) of the Permalloy rectangle 400×250×4 nm^3. The dashed lines correspond to the case of the absence of thermal fluctuations, and the solid line shows hysteresis cycles simulated in the presence of them. Rest magnetization configurations corresponding to the main remagnetization modes are shown in the inset. Calculation grid is $32 \times 20 \times 1$.

Our simulations show that for a low width W and a high enough aspect ratio $Q = L/W$, where L is the particle length, the simulated particles have almost rectangle hysteresis loops for both S- and C-like magnetization configurations. The magnetization process is rather simple for narrow particles and is governed by the creation and motion of charged Néel walls from the opposite short sides of the particle. They annihilate easily if the initial state is the S-state, but hardly for the C-state. The last effect leads to the difference in the bulk magnetization reversal switching field for wider particles, which may be significant for some sizes as illustrated by the dashed lines in Fig. 1. The energy of the S-like remanent state is mostly higher than the one of C-like for the zero bias magnetic field, but becomes lower for some non-zero magnetic field applied in the hard direction. The energy barrier separating these states decreases with increasing the driving field in the saturation direction.

The thermal inter-conversion of these two kinds of magnetization configurations for some bias and driving magnetic fields causes the switching instability of magnetization hysteresis loops during their cycling. The solid line in Fig. 1 shows the results of taking into account thermal fluctuations for the room temperature. We simulated the permalloy particle re-magnetization using alternative magnetic field $H = H_0 \cos(2\pi t/t_\Omega)$ of the periodicity $t_\Omega = 2$ μsec and the steady bias magnetic field in the transverse direction 1.5 Oe. Simulations show that the switching magnetic field of the particle changes accidentally during hysteresis cycles by 30%. For this, the coercivity decreasing connected with the single-mode Néel Brown instability does not exceed 10%. So, one can see that the giant thermal instability of the nano-scale particle switching may be observed long before the super-paramagnetic limit [5].

4. Edge pinning effect and minor hysteresis branches

For wide film elements 800 × 600 × 4 nm, a hysteresis curve becomes more complicated for both S-mode and C-mode. It is because of the effect of lateral edge magnetization pinning. The example of this effect influence on the hysteresis loop simulated for the particle having the S-remanent state is shown in Fig. 2.

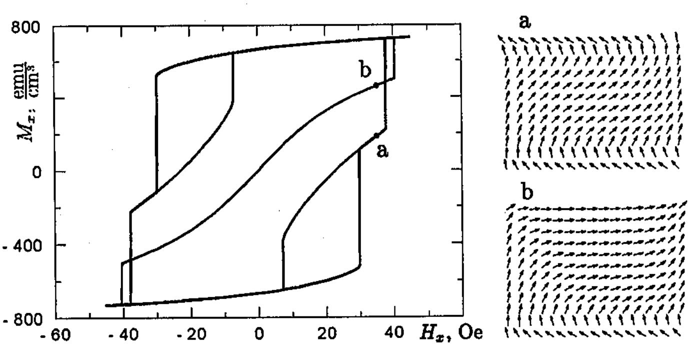

Fig. 2. Major and minor hysteresis loops of the particle 800 × 600 × 4 nm^3 in the case of edge pinning effects. The inset: characteristic magnetization configurations for (a) two-side pinning and (b) one-side pinning. Calculation grid is 64 × 48 × 1.

Additional Barkhausen steps arise on the hysteresis loop for magnetic fields higher than the bulk switching field H_c. They originate from the creation of Néel walls pinned by the edge magnetic stray fields on lateral sides of the particle. There may be either two Néel walls pinned on opposite sides of the element or only a single wall pinned on one side as shown in the inset of Fig. 2. These states are responsible for the corresponding minor loops shown in Fig. 2.

The de-pinning magnetic field H_{d1} for the two pinned walls is less than that for the single one, i.e. $H_{d1} < H_{d2}$, because the exchange pressure is higher in the first case. One-side edge pinning exists for all magnetic fields inside the major hysteresis loop, while the two-side pinning state disappears if the driving magnetic field closes zero.

De-pinning magnetic field determining the switching of the pinned state to the saturated one depends on the geometric parameters and on the bias magnetic field applied in the transverse direction. The dependence of the magnetization edge de-pinning fields is slighter than the dependence of the bulk coercivity H_c, which is more sensitive to the aspect ratio of the particle. For some particle sizes, there is the region, where the bulk coercivity exceeds the edge pinning field, and the hysteresis loop becomes nearly of the rectangular shape.

The two-side pinning state is switched to the saturated state for the uniform magnetic driving field. But if the gradient of the magnetic field does exist in the transverse direction, then the one-side pinning state is formed before the particle is switched into the saturation. Thermal fluctuations may cause the switching from a symmetric to an asymmetric state. Stray magnetic field gradients arise often in an array of elements. They can induce one-side edge pinning of magnetization during its switching for some bias magnetic fields. Simulations show that the dispersion of elements hysteresis parameters in the array leads to the great number of minor loops having different slope in the presence and in the absence of the edge pinning effect. In the absence of pinning and for the low enough hard bias fields, array minor hysteresis loops are close to the rectangular shape. But for higher bias fields, the appeared edge pinning effect leads to the crucial change of the minor loops of the array's hysteresis.

The considered effect of magnetization edge pinning is important, not only for the single layer particles, but also because it may be observed in the thick layer of the three-layer structure. The role of bias field plays there the stray magnetic field created by the thin layer.

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References

[1] M.E. Shabes, *J. Magn. Magn. Mater.* **95**, 249 (1991).

[2] Y. Zheng, J.-G. Zhu, *J. Appl. Phys.* **81**, 5471 (1997).

[3] E.D. Boerner, H.N. Bertram, *IEEE Trans. Magn.* **33**, 3052 (1997).

[4] Y. Nakatani, Y. Uesaka, N. Hayashi, *Jpn. J. Appl. Phys.* **28**, 2485 (1989).

[5] W.F. Brown, Jr., *Phys. Rev.* **130**, 1677 (1963).