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КОМПЬЮТЕРНЫЕ ТЕХНОЛОГИИ В ФИЗИКЕ

THE STATISTICAL RESPONSE TO THE POINT DEFECT IN THERMALLY ACTIVATED REMAGNETIZATION OF MAGNETIC DOT ARRAY

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The regular square-shaped 5×5 segment of magnetic dots is simulated in cyclic magnetic field under the simultaneous thermal activation. The simulation based on stochastic Landau–Lifshitz–Gilbert equation uncovered remarkable differences between statistics of defect-free and defect-including geometries.

Проведено моделирование квадратного 5×5 сегмента магнитных точек в циклическом магнитном поле при одновременной тепловой активации. Моделирование на основе стохастического уравнения Ландау–Лифшица–Гильберта показало значительные отличия между статистикой в геометрии без дефектов и с дефектами.

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INTRODUCTION

Magnetic dot arrays (MDA) [1] are systems of the magnetic nanoelements with periodic highly regular geometry. The MDA concept is productive in creating new and improved physical ideas. The new magnetic properties follow from the interplay between intra-dot and inter-dot ordering at small intra-dot and large inter-dot scales. The enormous ratio of free dot surfaces with respect to the volume causes that many of macroscopic MDA properties significantly differ from the classical bulk magnetic materials. In practice the periodic geometry is not ideal and all the magnetic properties are in some manner affected by the technological defects.

What has been found to be relevant for our previous defect studies is that the square lattice seems to be more sensitive to remagnetization changes than the triangular ones. In that case the defect can model the local magnetostatic deviation of the magnetostatic field. Despite of these practical arguments, even one fundamental reason for a more pronounced investigation exists that is the magnetostatic nature of inter-dot interaction responsible for measurable impact of magnetostatic defects. Several properties of the system were demonstrated by the previous quasi-static zero-temperature MDA simulations [2]. The conclusion from this study has been that differences in hysteresis loops are not very pronounced despite of the remarkable changes in the local arrangement of dots. More profound differences were found for relaxation modes.

In the present study we investigate the additional factor — thermal activation. The basic reason is that the thermal noise is one of the key factors needed to keep more realistic description of magnetic properties of MDA. When the noise is considered, the single hysteretic event looses its importance and thus the statistical viewpoint is needed to keep the reproducible information from multitude of remagnetization events. More specifically, the distributions of magnetization returns, remanent magnetizations and coercitive fields are studied in combination with defect-including and defect-free geometries, respectively.

1. MODEL

We used here the elementary model of MDA where each dot is simply represented by the point magnetic dipole. The model is justified for monodomain isotropic nearly spherical ferromagnetic particles, separated by a sufficient lattice spacing several times exceeding the dot diameter. We assume here that dots are ordered into 2D square superlattice of square $L \times L$ shape on the nonmagnetic substrate. The dots are described by 3D effective continuous magnetic moments $\{\mathbf{m}_i\}$ enumerated by $i = 1, 2, \ldots, L^2$ indexes. In the case of sufficiently small dots the inter-dot interactions can be simply approximated by the dipolar effective field

$$\mathbf{h}_i^{\mathrm{dip}} = - \sum_{j=0, j\neq i}^{L\times L} \frac{\mathbf{m}_j r_{ij}^2 - 3\mathbf{r}_{ij}(\mathbf{m}_j \cdot \mathbf{r}_{ij})}{r_{ij}^5}, \tag{1}$$

where $\mathbf{r}_{ij}$ is the distance between ith and jth dot in lattice-spacing units a for the moments normalized as $|\mathbf{m}| = 1$; the field is measured in the $H_u = VM_s(4\pi a^3)^{-1}$ units including the dot volume V and saturated magnetization of dots material M_s. The nonmagnetic point-defect is, in our consideration, located at MDA center represented by the zero $|\mathbf{m}^{\mathrm{def}}_{i=\mathrm{center}}| = 0$ moment. The dynamics of magnetic moments is described by the stochastic Landau–Lifshitz–Gilbert equation (see, e.g., [3])

$$\frac{d\mathbf{m}_i}{d\tau} = -\mathbf{m}_i \cdot \mathbf{h}_i^{\mathrm{eff}} - \alpha \mathbf{m}_i \cdot \mathbf{m}_i \cdot \mathbf{h}_i^{\mathrm{eff}}, \tag{2}$$

where the effective field $\mathbf{h}_i^{\mathrm{eff}} = \mathbf{h}_i^{\mathrm{dip}} + \mathbf{h}^{\mathrm{ext}} + \mathbf{h}_i^{\mathrm{th}}$ consists of the dipolar, external field and thermal component, respectively; α is dimensionless damping parameter; τ is the time in $t_u = 4\pi a^3[\gamma(1+\alpha^2)VM_s]^{-1}$ units, where γ is the gyromagnetic ratio. The stochastic thermal field $\mathbf{h}_i^{\mathrm{th}}$ is assumed to be a Gaussian random process with the following statistical properties [4]:

$$\langle h_{i,\xi}^{\mathrm{th}}(\tau)\rangle = 0, \quad \langle h_{i,\xi}^{\mathrm{th}}(\tau) h_{j,\eta}^{\mathrm{th}}(\tau')\rangle = 2\sigma^2 \delta_{ij}\delta_{\xi\eta}\delta(\tau - \tau'), \tag{3}$$

where $\xi, \eta \in \{x, y, z\}$ and i, j are the site indexes; σ^2 is the noise amplitude. According to fluctuation-dissipation relation [3, 5], the factor σ is linked to the temperature T

$$\sigma^2 = \frac{\alpha}{1+\alpha^2}\frac{T}{T_0}, \quad T_0 = \frac{\mu_0 V^2 M_s^2}{4\pi k_B a^3}, \tag{4}$$

where T_0 is the characteristic temperature scale.

2. NUMERICAL SIMULATION

The properties of odd-L MDAs have been studied for time varying external field which has been applied along one of the main axis of $\mathbf{e}_x$ array $\mathbf{h}^{\rm ext}(\tau) = (h_x^{\rm ext}(\tau), 0, 0)$. We have focused on the behaviour of the magnetization projection $M_x = \dfrac{1}{L^2}\sum_{i=1}^{L^2} \mathbf{m}_i \cdot \mathbf{e}_x$. Due to inhomogeneity of the remagnetization process it could be useful to compare the integral magnetization effect with local loops taken from different geometric regions of MDA. The dots surrounding the center, edges, and corner have been studied separately. The numerical integration of differential equations (2) has been carried out via predictor-corrector Heun scheme [3]. The remagnetization process in the saw-type field regime has been cycled within the bounds $h_x^{\rm ext} \in \langle -h_{\max}, h_{\max}\rangle$. The bound $h_{\max} = 3$ has been chosen that was verified is sufficient to keep nearly saturated magnetic state. In the regime we applied each time integration step $\Delta\tau = 5 \cdot 10^{-3}$ is accompanied by the change in the external field $\Delta h_x = 10^{-5}$. Both quantities define the sweeping rate $v_h = \Delta h^{\rm ext}(\Delta\tau)^{-1} = 2 \cdot 10^{-3} v_u$, where $v_u = H_u(t_u)^{-1}$. The repeated sweeps and counter-sweeps have been used to generate statistics of 800 remagnetization loops.

In our simulations we focus on MDA of $L = 5$. In that case the defect was localized at the position $(3, 3)$. From the comparison of the mean hysteresis loops of the MDAs with defect and without defect it follows that defect affects not only its nearest neighbors but also MDA corners and edges that is a typical consequence of magnetostatic coupling. In addition, we have observed that impact of the defect depends on the temperature and dependence kept by this way have to be non-monotonous. Surprisingly, the differences between defect-including and defect-free geometry, respectively, become more pronounced when the temperature is higher than zero. On the other hand the irreversible changes have to be destroyed by temperature fluctuations.

3. STATISTICAL PROPERTIES OF DISTRIBUTIONS

The remagnetization noise has been analyzed in the representation of the returns $\Delta m = m(\tau + 100\Delta\tau) - m(\tau)$. To keep the averages, the magnetization returns were collected separately for increasing ($\Delta h_x^{\rm ext} > 0$) and decreasing ($\Delta h_x^{\rm ext} < 0$) regimes. In Fig. 1 the probability density function (pdf's) is depicted. As can be seen from these figures the shape of pdf's are clearly defect-sensitive. The differences can be quantitatively characterized by leptocurticity $K = \dfrac{\langle \Delta M_x^4\rangle}{3\langle \Delta M_x^2\rangle^2}$ and skewness parameter $S = \dfrac{\langle |\Delta M_x|^3\rangle}{\langle |\Delta M_x|\rangle^3}$. Their values are listed in Table 1. The supplementary information is obtained from the statistics of the coercitive fields extracted from the points of zero magnetization. The procedure yields pdf of the $h_{\rm coerc}$ events. Similarly, the remanent magnetization events has been collected from the zero-field crossings. The pdf's are listed in Fig. 2. Mean values of coercitive fields and remanent magnetizations are noted in Table 2.

The defect-sensitivity is sufficiently remarkable. The numerical stability of distributions has been tested for different time steps. After the replacements $\Delta\tau \to \Delta\tau/2$ $\Delta h_x \to \Delta h_x/2$ the sweeping rate remains conserved. Practically it means that statistics of magnetization

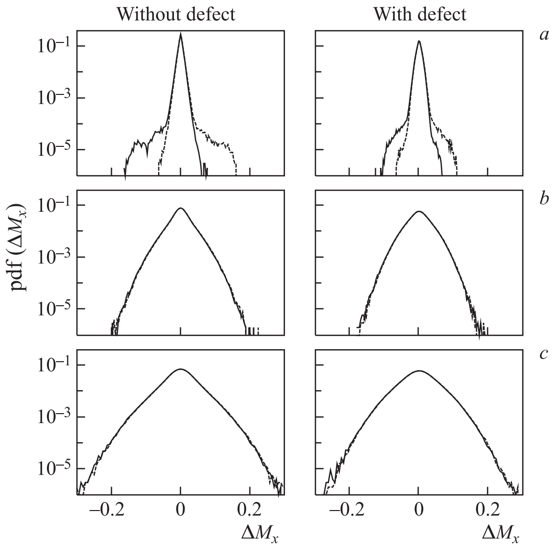

Fig. 1. The probability density function (pdf) investigated separately for two sweeping regimes $\Delta h_x^{\text{ext}} > 0$ (dashed line) and $\Delta h_x^{\text{ext}} < 0$ (solid line). The comparison of array without defect (left) and with central (3, 3) point defect (right). Calculated for temperatures: *a*) $T = 0.01T_0$; *b*) $T = 0.2T_0$ and *c*) $T = 0.5T_0$

Table 1. **The leptocurticity K and skewness S obtained for loops at different temperatures. The largest effect is observed within the small temperature region**

T/T_0	Without defect		With defect	
	K	S	K	S
0.01	11.952	11.845	3.162	5.580
0.10	1.705	5.245	1.245	4.020
0.20	1.613	5.104	1.285	4.004
0.50	1.577	4.834	1.283	4.002
1.00	1.420	4.280	1.282	3.925

Table 2. **Coercitive fields and remanent magnetizations**

T/T_0	Without defect		With defect	
	$\langle \lvert h_{\text{coerc}} \rvert \rangle$	$\langle \lvert M_{\text{rem}} \rvert \rangle$	$\langle \lvert h_{\text{coerc}} \rvert \rangle$	$\langle \lvert M_{\text{rem}} \rvert \rangle$
0.01	0.540	0.183	0.495	0.092
0.1	0.324	0.174	0.458	0.089
0.2	0.158	0.166	0.362	0.085
0.5	0.045	0.091	0.113	0.056

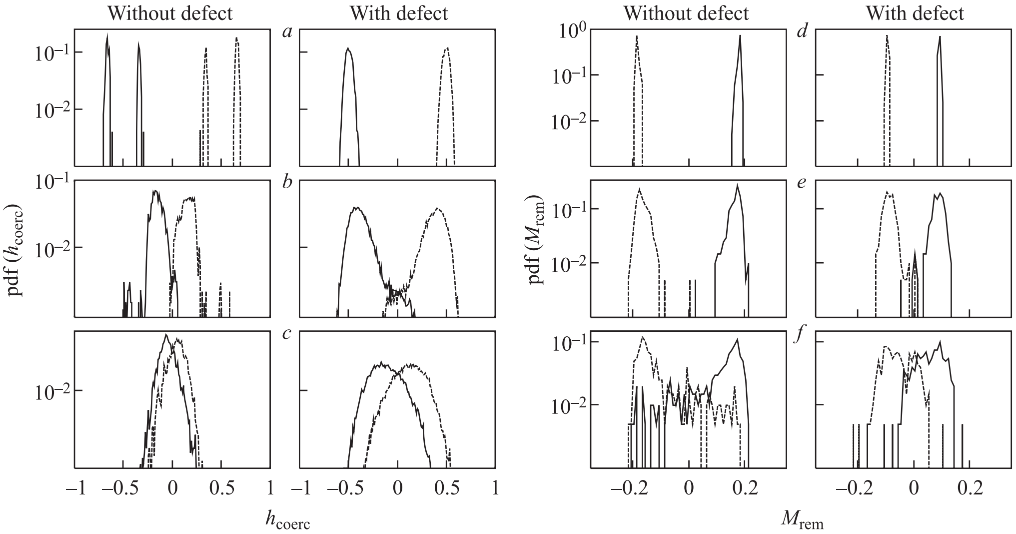

Fig. 2. The distribution of the coercitive fields (*a–c*) and remanent magnetizations (*d–f*) derived from the part of stochastic hysteresis loops. The dashed line belongs to $\Delta h_x^{\mathrm{ext}} > 0$ branch; $\Delta h_x^{\mathrm{ext}} < 0$ branch is depicted by the solid line. The loops without (left) and with central point defect (right) are compared. The statistics is collected for temperatures $T = 0.01T_0$ (a, d); $T = 0.2T_0$ (b, e) and $T = 0.5T_0$ (c, f)

returns $M_x(t + 200\Delta\tau) - M_x(t)$ could be nearly equivalent to the statistics obtained for differences including 100 time steps. The numerical testing confirms the most remarkable differences between approaches occur at the tails of ΔM_x distributions.

CONCLUSIONS

The elementary model of MDA including single central defect has been studied. The elementary dipolar structure of the model deeply contrasts with a high complexity of emerging remagnetization loops. High sensitivity of investigated nanodevice clearly implies relevance for sensorial and defectoscopic applications. The extension of simulations to high temperatures is not straightforward. In that case the interplay of thermal and magnetostatic terms lies in the region of larger anisotropic dots arranged into dense arrays. Treatment of such conditions requires adaption of micromagnetic models taking into account all relevant intra-dot terms.

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REFERENCES

1. *Martín J. I. et al.* // J. Magn. Magn. Matt. 2003. V. 256. P. 449.
2. *Horváth D. et al.* // J. Magn. Magn. Matt. (in press).

3. *Scholz W., Schrefl W., Fidler J.* // J. Magn. Magn. Matt. 2001. V. 233. P. 296.

4. *Li Z., Zhang S.* // Phys. Rev. B. 2003. V. 68. P. 024404.

5. *García-Palacios J. L., Lázaro F. J.* // Phys. Rev. B. 1998. V. 58. P. 14937.

6. *Kayali M. A., Saslow W. M.* // Phys. Rev. B. 2004. V. 70. P. 174404.