Proceedings of the CSMAG'07 Conference, Košice, July 9–12, 2007

Defect Sensitivity of Magnetic Dot Arrays Influenced by Thermal Activation and Intradot Anisotropy

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The influence of non-magnetic central node defect on magnetic hysteresis of regular square-shaped segment of magnetic dot array with perpendicular uniaxial anisotropy under the thermal activation was investigated via computer simulations based on stochastic Landau-Lifshitz-Gilbert equation. The aim of this study is to point out the simultaneous effect of anisotropy and thermal activation to the dynamical properties of magnetic dot arrays.

PACS numbers: 61.80.Az, 74.25.Fy, 74.72.Bk, 02.70.Bf

1. Introduction

Magnetic dot arrays (MDAs) [1] are nanoscaled monolayer structures consisting of the identical magnetic nanoparticles, called dots, which are periodically ordered on a non-magnetic substrate. MDAs are interesting, partly because of their properties, that essentially differ from those of the bulk materials. The concept of MDAs is associated with variety of applications like magnetic field sensors [2] or reading heads of magnetic-disk data-storage devices [3].

The technology of fabrication of MDAs [4] has been perfected to an excellent degree in the past few years. However, in practice, an occurrence of technological defects is still frequent [5]. This is the reason we study how the imperfection in form of the single-dot vacancy in the center of MDA pattern affects remagnetization processes. In order to understand defect consequences, two distinct MDA arrangements — *defect-free* (DF) and *defect-including* (DI) — were simulated and its properties were compared.

Our present study is closely related to our previous work on isotropic model [6]. A key aim of this paper is to investigate the effect of perpendicular uniaxial out-of-plain anisotropy of dots.

2. Model

In this section we shortly review the dipolar model of monodomain ferromagnetic particles on regular square lattice $L \times L$ separated by a lattice spacing a.

The magnetic state of i-th dot is described by the effective rescaled 3D magnetic moment $\boldsymbol{m}_i$ normalized as $|\boldsymbol{m}_i| = 1$. The effective field in i-th dot of MDA is

$$\boldsymbol{h}_i^{\text{eff}} = -\sum_{j=0, j\neq i}^{L\times L} \frac{\boldsymbol{m}_j r_{ij}^2 - 3\boldsymbol{r}_{ij}(\boldsymbol{m}_j \cdot \boldsymbol{r}_{ij})}{r_{ij}^5} + k\mathrm{m}_{i,\mathrm{z}}\boldsymbol{e}_{\mathrm{z}} + \boldsymbol{h}^{\text{ext}}, \tag{1}$$

where the first term describes dipolar coupling between dots of distance $\boldsymbol{r}_{ij}$. The second term introduces uniaxial anisotropy specified by dimensionless constant k; $\boldsymbol{e}_{\mathrm{z}} = (0, 0, 1)$ is the direction vector. Finally, the third term of $\boldsymbol{h}_i^{\text{eff}}$ is the external magnetic field. The field is measured in the $H_0 = VM_{\mathrm{s}}(4\pi a^3)^{-1}$ units including the dot volume V and saturated magnetization M_{s}. The magnetic moment of defect is fixed to zero. The dynamics of magnetic moments is described by the stochastic Landau–Lifshitz–Gilbert equation [7]:

$$\frac{\mathrm{d}\boldsymbol{m}_i}{\mathrm{d}\tau} = -\boldsymbol{m}_i \times (\boldsymbol{h}_i^{\text{eff}} + \boldsymbol{h}_i^{\text{th}}) - \alpha \boldsymbol{m}_i \times \left[\boldsymbol{m}_i \times (\boldsymbol{h}_i^{\text{eff}} + \boldsymbol{h}_i^{\text{th}})\right], \tag{2}$$

where α is the dimensionless damping parameter; τ is the time in $t_0 = 4\pi a^3[\gamma(1+\alpha^2)VM_{\mathrm{s}}]^{-1}$ units and γ is the gyromagnetic ratio; $\boldsymbol{h}_i^{\text{th}}$ is the stochastic Langevin thermal noise with statistical properties $\langle h_{i,\xi}^{\text{th}}(\tau)\rangle = 0$, $\langle h_{i,\xi}^{\text{th}}(\tau) h_{j,\eta}^{\text{th}}(\tau')\rangle = 2D\delta_{ij}\delta_{\xi\eta}\delta(\tau - \tau')$, where $\xi, \eta \in \{x, y, z\}$ and i, j are the site indexes; $D = [\alpha/(1+\alpha^2)](T/T_0)$ is the noise amplitude, dependent on temperature T measured in $T_0 = (\mu_0 V^2 M_{\mathrm{s}}^2)/(4\pi k_{\mathrm{B}} a^3)$ units.

3. Remagnetization process

We have studied behavior of DF and DI MDAs in the time varying external magnetic field applied in parallel way to one of the main MDA axes $\boldsymbol{h}^{\text{ext}}(\tau) = (h_{\mathrm{x}}^{\text{ext}}(\tau), 0, 0)$. The component $h_{\mathrm{x}}^{\text{ext}}(\tau)$ has been cycled within the bounds $-h_{\max} <$

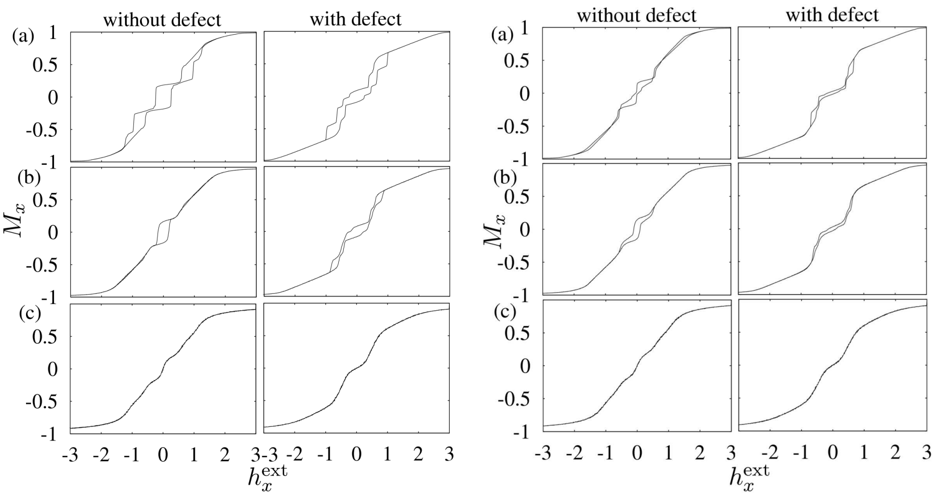

Fig. 1. The averaged hysteresis loops obtained for DF and DI MDAs with $k = 1.7$ (left) and $k = 2.0$ (right) at temperatures (a) $T = 0.01T_0$, (b) $T = 0.1T_0$, (c) $T = 0.5T_0$.

$h_{\rm x}^{\rm ext}(\tau) < h_{\max}$, where $h_{\max}$ hase to be enough to saturate MDA. It has been verified that $h_{\max} = 3$ is sufficient. The quantity of our interest has been the magnetization projection $M_x = (1/L^2)\sum_{i=1}^{L^2} \boldsymbol{m}_i \cdot \boldsymbol{e}_x$. The simulation started from saturated state $M_x = 1$ and $h_x^{\rm ext} = h_{\max}$. In the remagnetization regime each time-integration step $\Delta\tau = 10^{-2}$ is accompanied by the elementary change of the external field $\Delta h_x^{\rm ext} = \pm 10^{-6}$. Numerical integration of Eq. (2) has been performed using stochastic Heun scheme [7]. For further details of numerical approach see [6]. All of our numerical analysis is limited to MDA of size $L = 5$, and dot material $\alpha = 0.1$. In Fig. 1 we show mean hysteresis loops obtained by averaging of 600 stochastic remagnetization events. Obviously, by increasing the temperature, the hysteresis vanishes. The magnetization reversal is accompanied by the complex collective behavior of dot moments. Rather slow magnetization moves are separated by abrupt irreversible jumps. The dynamical impact of defect is characterized here by the temperature dependence of the ratio $A_{\rm DI}/A_{\rm DF}$ of DI and DF mean areas of hysteresis loops (see Fig. 2).

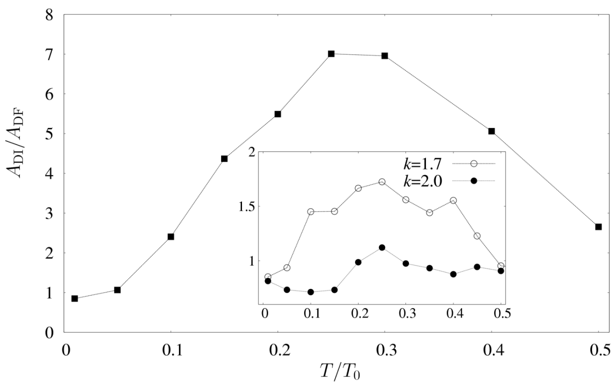

Fig. 2. The ratio of the areas of DI and DF hysteresis loops as a function of the temperature. In the main frame one can see the non-anisotropy case ($k = 0$). Less pronounced effect of extremal $A_{\rm DI}/A_{\rm DF}$ caused by the out-of-plane anisotropy ($k > 0$) is shown in the inset.

4. Conclusion and discussion

The numerical simulations have confirmed that the presence of non-magnetic central node defect on MDA segment of square lattice affects significantly the dynamical properties of MDA, which clearly follows from Fig. 1. According to Fig. 2 the including of thermal activation brings not only more realistic view point, but it enhances a chance to identify point defect. Quantitatively, the optimum for defect detection is temperature $T_{\max} \simeq 0.25T_0$. The results indicate that the peak of $A_{\rm DI}/A_{\rm DF}$ decreases with k increasing, but the non-monotonous course of this temperature dependence reassembles the isotropic case. In addition, $T_{\max}$ does not change significantly with k. In summary, our results confirm that various defect detection methods proposed in [6] could be generalized to MDAs consisting of anisotropic dots, however, the sensitivity of defect detection becomes disputable in highly anisotropic cases.

Acknowledgments

Authors would like to thank for financial support through grants VEGA 1/2009/05, APVT-51-052702, APVV-LPP-0030-06 and MVTS POL/SR/UPJS07.

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