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Frustration and finite size effects of magnetic dot arrays

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Abstract

The static magnetic order and dynamic magnetic response of arrays of small ferromagnetic dots are studied, and the effects of lattice geometry are examined through weak dipolar coupling between magnetic dots. Array size and applied field orientation are found to have important effects on the magnetization process. © 1998 Elsevier Science B.V. All rights reserved.

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The technology to fabricate independent magnetic wire and dot structures with physical extensions on the submicrometer and nanometer length scale is currently an area of intense interest [1, 2]. Dipolar fields in some of these structures can be comparable to cubic anisotropy fields and will strongly affect magnetization processes. In this paper we discuss the effects of finite array sizes on magnetization reversal. We also show how weak dipolar interactions can determine the nonlinear response characteristics of high-frequency behavior.

We construct a theory for examining dipolar effects by numerically solving the time-dependent Landau–Lifshitz equations of motion for an array of interacting magnetic dots. This approach can be used to compute time-dependent relaxations to static order as well as to investigate the dynamic properties of the array. In this paper we assume single-domain particles and concentrate on inter-dot interactions. For simplicity, the dots are assumed to be uniformly magnetized, although effects of field-dependent dot magnetization can be important [3].

The dots are assumed smaller than an exchange length so that the average magnetization of a dot is reasonably approximated by a single effective magnetic moment. The equation of motion of a dot magnetic moment $\boldsymbol{m}$ at position $\boldsymbol{r}$ in the array is then

$$\mathrm{d}\boldsymbol{m}(\boldsymbol{r})/\mathrm{d}t = \gamma \boldsymbol{m}(\boldsymbol{r}) \times \boldsymbol{H}(\boldsymbol{r}) + \alpha \boldsymbol{m}(\boldsymbol{r}) \times \boldsymbol{m}(\boldsymbol{r}) \times \boldsymbol{H}(\boldsymbol{r}). \quad (1)$$

Here γ is the gyromagnetic ratio, α controls the rate of dissipation, and $\boldsymbol{H}$ is the average effective field acting at position $\boldsymbol{r}$. Contributions to $\boldsymbol{H}$ are a static applied field H_0, a time dependent driving field $\boldsymbol{h}_\omega$ with frequency ω, and a time dependent dipole field $\boldsymbol{h}_\mathrm{d}$ due to all the other dots in the array. All contributions to the anisotropies in the dots are assumed to be described by a single uniaxial anisotropy K with an easy-axis directed normal to the dot array plane, as would be appropriate for cylindrical dots. The set of coupled equations for a square array of dimension N is solved numerically using a second-order Runge–Kutta method.

The dipole strength is determined by the physical structure of the array and is characterized by a parameter h_d defined as $\pi h R^2/a^3$, where h and R are the height and radius of a dot cylinder, and a is the center-to-center distance between nearest-neighbor dots. All parameters are presented as ratios with respect to M_o, the magnetization of the dot material.

Effects of applied field orientation are shown in Fig. 1 for a 3×3 square array of dots with $h_\mathrm{d} = 0.5$. The anisotropy is -4π corresponding to a preferred in-plane orientation of the dots. In Fig. 1 the average magnetic moment of the dot array in the direction of a static applied field is shown for the field aligned parallel to an array edge, and for the field aligned along a diagonal. In

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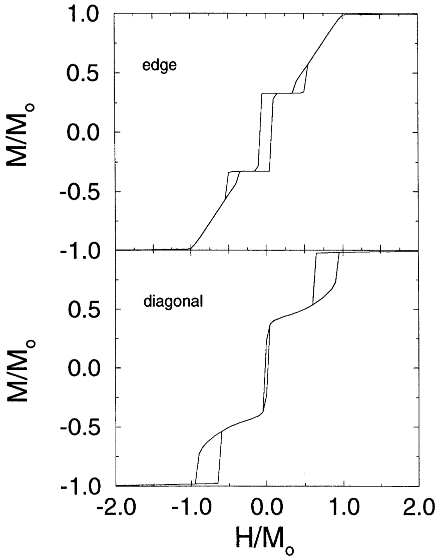

Fig. 1. Magnetization loops for a 3×3 square in-plane magnetized dot array. The applied field is aligned parallel to an array edge in the top panel, and along a diagonal in the bottom panel.

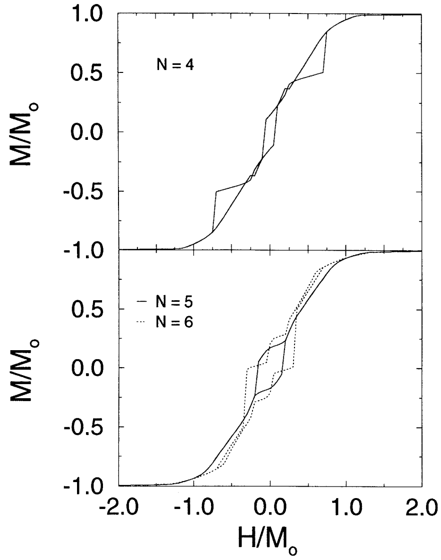

Fig. 2. Magnetization loops for in-plane magnetized arrays with even and odd numbers of dots and the field aligned parallel to an array edge.

both cases a uniformly magnetized state for the *array* is unstable in the absence of a field. Below the saturation field, the dot moments rotate in order to minimize magnetostatic energies originating from uncompensated magnetic poles at the array edges.

When the field is applied along an array edge, all four corner moments rotate slightly just below saturation. The effect of these corner moment rotations can be seen in Fig. 1 as a very small reduction of the average array moment from complete saturation. When the field is applied along a diagonal, the corner moments align with the field and the moments at the side centers rotate. This provides different initial conditions for futher rotations of the array moments as the field is reduced and is responsible for the effects of field orientation on the hysteresis. We note that the the results shown in Figs. 1 and 2 are with the field not directly along an array edge or diagonal, but instead misaligned 0.1° away in order to avoid the states that are unstable with respect to small misalignments of the applied field.

Even or odd N also has a strong effect on the shape of the magnetization loops for small N. This is shown in the upper panel of Fig. 2 where the average moment for a 4×4 square array of dots is shown as a function of field applied along an array edge. As N is increased, the distinction between even and odd becomes less pronounced, and the minor hysteresis loops are lost. These trends are apparent in the lower panel of Fig. 2 where the average moments for a 5×5 and 6×6 square arrays are shown.

It is interesting to note that the edge effects studied here for small arrays could be used to control the size of the coercive and saturation fields for dot array magnetizations. This can be seen in the examples shown in Fig. 2 by noting the increase in the saturation field with increasing N. Simulations on perpendicularly magnetized dot arrays have shown that array size effects on saturation and coercive fields are especially important for dots with large magnetic anisotropies.

Finally, we note that dipolar coupled magnet dot arrays display interesting and unusual high-frequency nonlinear dynamics. Work on this aspect of magnetic dot arrays is currently in progress.

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