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Influence of the properties of soft collective spin wave modes on the magnetization reversal in finite arrays of dipolarly coupled magnetic dots

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ABSTRACT

Magnetization reversal in finite chains and square arrays of closely packed cylindrical magnetic dots, having vortex ground state in the absence of the external bias field, has been studied experimentally by measuring static hysteresis loops, and also analyzed theoretically. It has been shown that the field B_n of a vortex nucleation in a dot as a function of the finite number N of dots in the array's side may exhibit a monotonic or an oscillatory behavior depending on the array geometry and the direction of the external bias magnetic field. The oscillations in the dependence $B_n(N)$ are shown to be caused by the quantization of the collective soft spin wave mode, which corresponds to the vortex nucleation in a finite array of dots. These oscillations are directly related to the form and symmetry of the dispersion law of the soft SW mode: the oscillation could appear only if the minimum of the soft mode spectrum is not located at any of the symmetric points inside the first Brillouin zone of the array's lattice. Thus, the purely static measurements of the hysteresis loops in finite arrays of coupled magnetic dots can yield important information about the properties of the collective spin wave excitations in these arrays.

1. Introduction

The properties of dipolarly coupled magnetic dots have attracted a lot of attention recently due to the possible applications of these dots in microwave signal processing, magnetic recording and medicine [1–5]. Depending on the shape and sizes, a magnetic dot can exist in different ground states: saturated single domain state, vortex state, multi-domain state, etc. [6–9]. The transition between these ground states can happen under the influence of an external bias magnetic field [10–12]. For example, a thin circular magnetic dot with submicron lateral sizes could exist in a vortex ground state at zero applied field, and with the application of a sufficiently large bias field the equilibrium static state of the dot changes reversibly to a saturated one.

If magnetic dots are combined into an closely packed array, their properties are affected by the magnetostatic (dipolar) interaction between the dots. As a result, the static magnetic state of a single dot in an array becomes dependent on the array's structure, i.e., on the distance between the dots and the structure of the array's lattice. In particular, in an infinite closely packed array of thin circular magnetic dots the magnetostatic interaction between the dots results in the decrease of both the vortex nucleation and annihilation fields, compared to the case of an isolated magnetic dot [13–15].

It should be noted that the magnetostatic interaction is long-range, so that not only the neighboring dots in an array could interact effectively. Consequently, one may expect that the static properties of a *finite* array, consisting of a relatively small number of dots, will depend not only on the interdot distances and lattice structure, but also on the number of dots in the whole array.

In this paper we investigate experimentally how the static properties, in particular, the vortex nucleation field B_n, in one- and two-dimensional finite arrays of magnetic dots depends on the total numbers of dots in the array. Naively, one might think that such a dependence should be trivial: an addition of a single dot or a single rows of dots to an array should lead to a monotonic increase of the magnetostatic interaction. This increase should result

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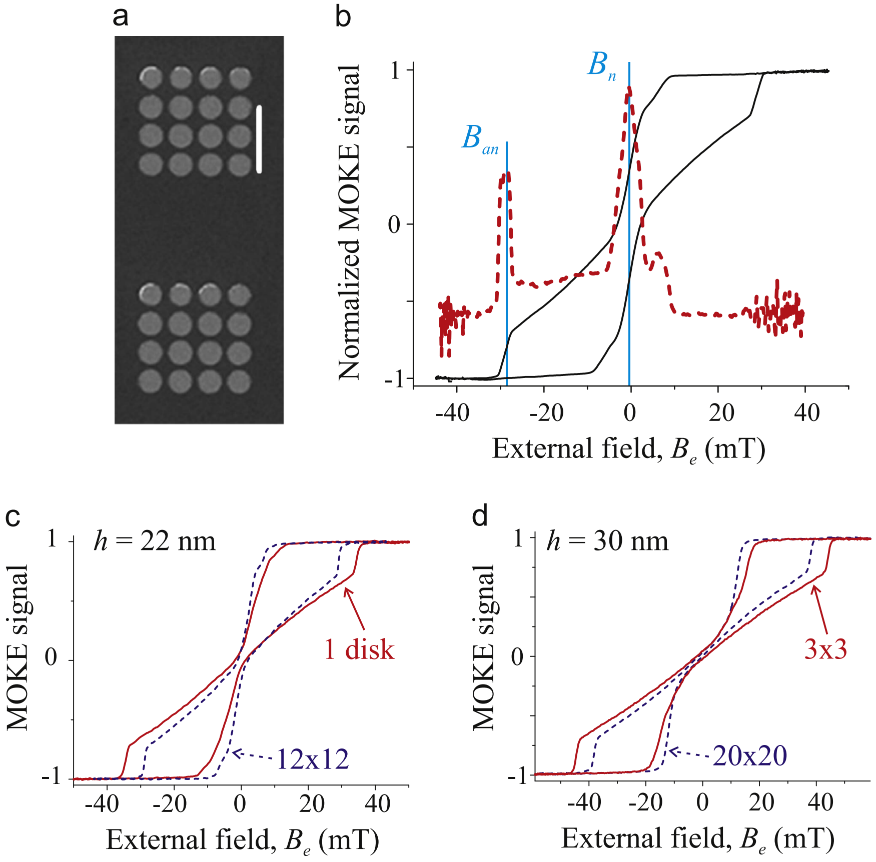

Fig. 1. (a) Scanning electron microscopy (SEM) images of two 4 × 4 square arrays of cylindrical magnetic dots. The thick white line of 2 μm defines the in-plane spatial scale; (b) magnetic hysteresis loop of a 20 × 20 array of cylindrical dots with thickness h=22 nm (solid black line). The external bias magnetic field was applied along the array's side. Dashed line shows the derivative dM/dB (in arbitrary units) of the upper part of the hysteresis loop (path from positive saturation to negative); (c) and (d) set of measured hysteresis loops for different array sizes N and dot thicknesses. The bias magnetic field was applied along the array's side.

in the stabilization of the saturated state [13], i.e. in the decrease in the magnitude of the vortex nucleation field. However, as we will demonstrate below, this simple picture is incorrect. In particular, in contrast with the naive expectations, non-monotonic dependence $B_n(N)$ of the vortex nucleation field on the array's sizes can be realized under certain conditions. This behavior is caused by the properties of collective spin-wave excitations in finite arrays and, in some sense, is analogous to the behavior of the ionization potential [16], polarizability [17], conductance [18] and magnetic moment [19] in small atomic clusters.

To study the impact of the finite array's sizes on the magnetization reversal we fabricated chains (1 × N dots) and square arrays ($N \times N$) of permalloy dots. Cylindrical dots with diameter D=600 nm and thicknesses h=22, 30 nm were arranged into a square lattice with edge-to-edge separation 200 nm (see Fig. 1(a)). The array's size N was varying from 2 to 20.

The measurements of the static hysteresis curves have shown that the magnetization reversal in all the studied samples is accompanied by the vortex nucleation and annihilation. The samples having 30 nm thickness show typical “double-triangle” hysteresis loops (Fig. 1(d)), while the large arrays of dots having 22 nm thickness show “open” hysteresis loop with negative nucleation field (Fig. 1(b)) – it is known that this difference results from the magnetostatic interaction between dots (see, e.g. [13]). The exact values of the critical fields corresponding to the nucleation of a vortex and its annihilation were determined from the derivative dM/dB (see Section 2 for details), and were measured as functions of the array's size N.

2. Sample fabrication and measurements

To fabricate arrays of magnetic dots we deposited the permalloy films having thicknesses 22 and 30 nm on the Si/SiO$_x$ substrates by means of d.c. magnetron sputtering in Ar atmosphere. The patterns of dot arrays were exposed by electron beam lithography with the following development in MIBK:IPA (1:3) solution. After lift-off in acetone the chains and square arrays of cylindrical dots with diameter D=600 nm and edge-to-edge separation 200 nm were fabricated. The samples' quality was checked by atomic force microscopy and scanning electron microscopy. The standard deviation of the dot size and interdot distance were found to be of the order of 1%.

The static hysteresis loops were measured by the magnetooptical Kerr effect (MOKE) magnetometer with laser wavelength 635 nm. To measure the MOKE signal from a whole array, the diameter of the laser spot was varied in a range from 5 to 20 μm for different arrays. Thus, the laser spot covered the whole $N \times N$ array of dots, and we measured the integrated signal from the whole array.

For the determination of the exact values of the vortex nucleation field we calculated the derivative dM/dB of the hysteresis loop averaged over 100 measurement cycles, and determined B_n from the position of the maximum of this derivative (see Fig. 1(b)). This method is well-known and widely used for the exact determination of critical fields in the case of complex hysteresis loops (see, e.g. [20,21]).

In Fig. 1(b) one can note another smaller peak at the position $B_e \sim 6$ mT. This peak corresponds not to a vortex nucleation, but to the formation of some quasi-uniform state in dots, e.g. C-state or