Interaction Effects in Switching of a Two Dimensional Array of Small Particles

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Abstract—**The magnetostatic interaction between elements of a regular two-dimensional array of rectangular garnet pixels has been investigated. The up- and down switching fields of an individual pixels, have been measured magnetooptically. The switching characteristics of a given pixel depends on the state of the neighbors. In this work the effect of the magnetization state of the first 5 coordination shells on a central, test pixel was investigated experimentally and numerically. The interaction field, i.e. the demagnetizing/ magnetizing effects, is calculated exactly and in the dipole approximation for 24 pixels surrounding the central pixel. A good agreement between experimental and numerical results has been obtained.**

I. Introduction

The effect of the magnetostatic interaction between the elements of a regular two-dimensional array of highly uniaxial rectangular garnet pixels has been investigated. The problem is relevant to the extremely high density magnetic recording on individual slablike or cylindrical particles, and in magnetization processes of isolated small magnetic particles. Due to the very high uniaxial anisotropy field, the magnetization of the individual pixels is normal to the film plane (z-direction), they have a rectangular hysteresis loop, with only two possible states of magnetization: "up" (along +z) and "down". As it was shown earlier [1,2], this system is a good model for studying the switching characteristics of Stoner-Wohlfarth like particles and Preisach models of magnetic hysteresis.

The pixels interact magnetostatically. The effective field acting upon a pixel depends on the state of the neighbors. Assuming the external magnetic field pointing in the $+z$ direction, each neighbor with a magnetization along $+z$ will *demagnetize* the pixels having $+\boldsymbol{M}$, and *magnetize* the neighbors with $-\boldsymbol{M}$. The case of the two-dimensional array is different from the 3-D case, where the particles above and below the "test" particle have a compensating effect.

In this work the effect of the magnetic state of the first 5 coordination shells (24 pixels) was investigated experimentally and numerically. First, the demagnetization tensor for an individual pixel is computed, followed by calculation of the interaction field acting on the center pixel from its neighbors. Finally, the relationship between the magnetization state of the neighbors and the interaction field on the central pixel is calculated using a statistical model.

II. Experiments

Rectangular islands (pixels) are etched in a single crystalline epitaxial magnetic garnet film grown on a non-magnetic GGG substrate. The size of the pixels is 42 μm x 42 μm x 3 μm, separated by 12 μm wide grooves. The 5 x 5 mm^2 sample contains about 10^4 pixels. The garnet has a high uniaxial anisotropy, and as a result, the pixels have two stable magnetic states "up" and "down". The up- and down switching fields of individual pixels, groups of pixels, major and minor hysteresis loops have been measured magnetooptically in a Faraday effect optical magnetometer. An arbitrary pixel was selected and the state of the neighbors (1st coordination shell: 4 neighbors side-by-side; 2nd shell: 4 at corners; 3rd shell- 4 at side; etc, see Fig. 1) was recorded. Initially the sample was saturated in negative direction ("down", dark contrast); and the selected "test" pixel was monitored until it switched "up" in an increasing external field, applied normal to the sample at $H = H^+$.

The average width of the individual *hysterons*, measured on hundreds of pixels, corresponds to the coercivity H_c=288 Oe on the major hysteresis loop. The distribution of the switching fields of the individual pixels follows a Gaussian, with a standard deviation of σ_c= 112 Oe.

The hysteresis loops of the individual pixels are shifted, due to the interaction with the surrounding pixels. This interaction is entirely magnetostatic and it arises from the "demagnetizing" or "magnetizing" effects of the neighbors. The average interaction field is H_{int}=23.4 Oe and σ_{int}=25.2 Oe.

III. Results and discussion

The system is illustrated in Fig. 1, where $\boldsymbol{r}$ is the distance of the "test" pixel (field point) from the nth neighbor (source point). In the model, five neighbors are considered, at distances from the

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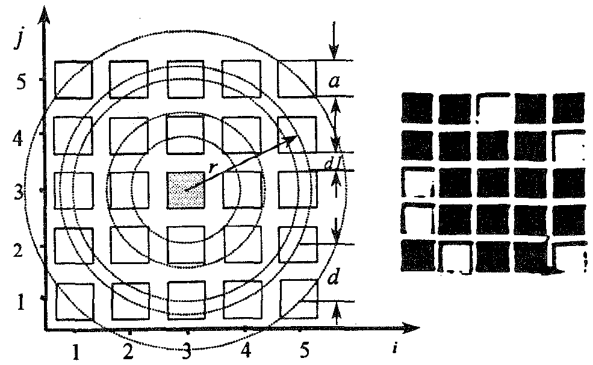

Fig. 1. The 2-D array of 25 pixels, corresponding to 5 coordination shells

center pixel of d, $\sqrt{2}d$, $2d$, $\sqrt{5}d$, $2\sqrt{2}d$. The external field is applied normal to the sample plane. The "test" pixel is at the center of the sample. The total magnetization is given by the difference of the number of "up" and "down" magnetized pixels. The effective field acting on a given pixels is the sum of the external field plus the vector sum of the interaction fields from the surrounding pixels.

A. Demagnetization tensor

The demagnetizing tensor $\boldsymbol{D}$ describes the interaction between any two pixels. It can be calculated by a surface integral or using the dipole approximation [3-5]. The field at pixel $\boldsymbol{i}$ due to pixel j, $\boldsymbol{H}_{ij}$, is expressed as:

$$\boldsymbol{H}_{ij}=\boldsymbol{D}(\boldsymbol{r}_{ij})\bullet\boldsymbol{M}_j \tag{1}$$

where $r_{ij}=r_i-r_j$ is the relative distance between pixels, and $\boldsymbol{M}_j$ is the magnetization of pixel $\boldsymbol{j}$. In the two dimensional case, the only relevant term is $D_{zz}(i, j)$. That means that the direction of magnetization of pixels and the applied field are normal to the sample plane. The demagnetization tensor element is defined by the surface integral

$$D_{zz}(i, j)=H_z/M_z=1/4\pi\oint_{sj}(z\bullet ds_j)/r_{ij}^3 \tag{2}$$

where s_j is the surface of pixel $\boldsymbol{j}$, z is the unit vector in z direction. Expanding the integrand into a Taylor series of $1/r_{ij}$ for large r_{ij}, the first term gives the dipole approximation:

$$D_{zz}(i,j)=-d^3/(4\pi r_{ij}^3) \tag{3}$$

where d is the size of the rectangular pixels.

Table I shows the values of D_{zz} calculated by these methods. The dipole approximation overestimates the exact surface integral calculation D_{zz} by 17.4 % for the first neighbor, and by 1.4% for the second neighbor; the deviation being negligible at larger distances.

TABLE I: Comparison between the dipole approximation and surface integral for demagnetizing tensor element D_{zz}(x,y,z) (units:10^{-3})

Shell	1st	2 nd	3 rd	4 th	5 th
Distance	d	$\sqrt{2}$ d	2 d	$\sqrt{5}$d	2$\sqrt{2}$d
Dipole	-79.58	-28.13	-9.947	-7.118	-3.517
Surf.Int	-67.79	-27.73	-9.848	-7.103	-3.513
Error, %	17.4	1.4	1.0	0.21	0.11

B. Interaction field

The interaction field at the center pixel is equal to the sum of demagnetizing fields from all neighbors. The demagnetizing field from pixel $\boldsymbol{j}$ at pixel $\boldsymbol{i}$ depends on the magnetization:

$$H_D(i, j)=D_{zz}(i, j)4\pi\boldsymbol{M}_j \tag{4}$$

The magnetization of the garnet is $4\pi M_j$=160 G. The field, acting on the test pixel, vs distance of the neighbors are shown in Fig. 2.

The interaction field at a given pixel, originating from all the other pixels is given by

$$\boldsymbol{H}_{int}=4\pi\boldsymbol{M}_s\boldsymbol{N}_{zz} \tag{5}$$

where $N_{zz}=\sum\sum D_{zz}(i, j)$, and the sign of $D_{zz}(i, j)$ is determined by the state of pixel $\boldsymbol{j}$. In fact, N_{zz} is (de)magnetizing factor. The measured up-switching field of the pixel is equal to:

$$H^+=H_{c0}-H_{int} \tag{6}$$

where H_{c0} is the coercivity of the central pixel, H_{c0} could only be measured on an isolated pixel, however, it can be determined from the measured H^+ and calculated H_{int}. For all the 24 neighbors switched "up", in other words, no neighbors in "down" state, H_{int}= -86 Oe, and from Fig. 5, H^+= 398 Oe, resulting in H_{c0}=312 Oe for that pixel. Fig. 3 shows the dependence of the up-switching

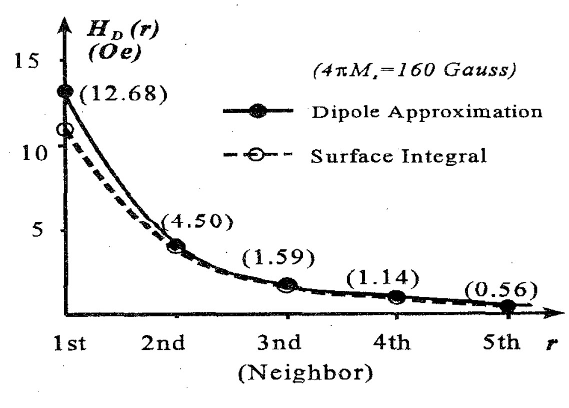

Fig. 2. The distance dependence of the demagnetizing fields at the central pixel, calculated by the surface integral (2) and dipole approximation (3) (The numbers on the curve are the dipole approximation)

field H^+ of a central pixel on the number n which are already switched, for the 5 coordination shells. Comparing and subtracting H^+ for different configurations, one can determine the contribution of each neighbor surrounding the central pixel. The slopes of the experimental curves are in good agreement with the numerical model, proving that the contribution from the 4th, 5th and further coordination shells is negligible.

C. Statistical model

It can be assumed that the distribution of the "up" and "down" pixels around the central pixel is random. For the system of 5 x 5 pixels of Fig. 1, there are 24 neighbors in five shells. Each pixel might be in 2 states. The first shell has 4 pixels; their states may be 0, 1, 2, 3 ,4 "up", i.e. five cases. For whole system, there are 5625 possible states of the 24 pixels. The probability of each individual state can be calculated, and the value of the interaction field can be determined based on the previous section. It is trivial, that there is only one state when all 24 pixels are "up" , their demagnetizing effect is maximal and equal to the sum from all pixels H_{int}=- 86 Oe. In a similar way, when all the 24 pixels are "down", they have a magnetizing effect with H_{int}=+86 Oe, added to the applied field. The number of cases is the maximum in the demagnetized state, when 12 pixels are "up", and the average interaction field is zero, although the standard deviation of H_{int} is the maximum, σ_{int}=38.81 Oe. Fig. 4 shows H_{int} and σ_{int} and the calculated probabilities of the statistical distributions. The calculated contributions of the up or down-magnetized pixels at different distances were compared to the measured values of the up-switching fields for clusters of 9 and 25 pixels. Fig. 5 gives the measured values of H^+ vs. the number of neighbors in the "down" state.

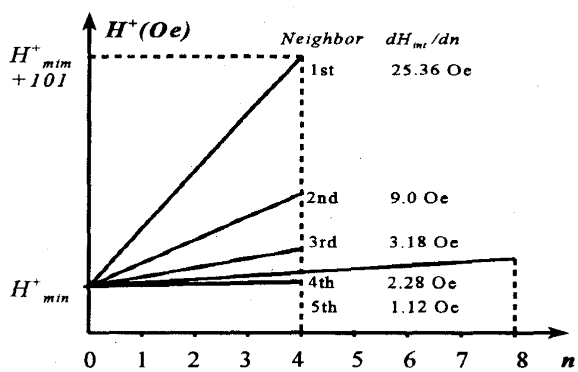

Fig. 3. The calculated contribution to the interaction field at the central pixel of pixels in oppositely magnetized states in different coordination shells

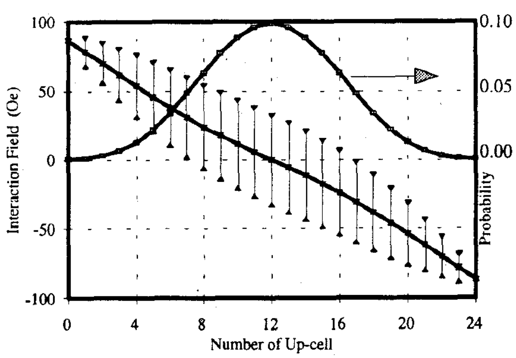

Fig. 4. The mean value and standard deviation of the interaction field at the center pixel vs the number of "up" neighbors; and the probability of having N neighbors magnetized "up".

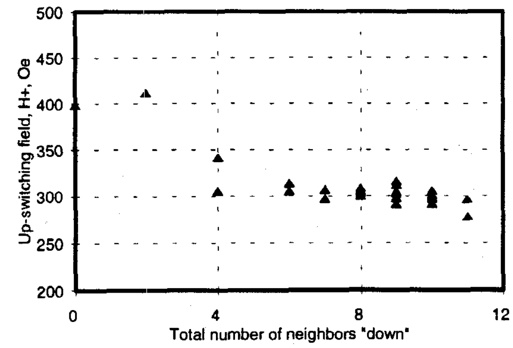

Fig. 5. Measured "up" switching field H^+ of the center pixel, depending on the number of neighbors magnetized "down"

IV. CONCLUSIONS

The interaction effects in a 2-D array between a central pixel and the surrounding 5 "coordination" shells have been measured magneto-optically by measuring the "up" and "down" switching fields of an individual pixel, depending on the magnetization state of the neighbors. For the numerical calculation of the interaction field, the demagnetizing tensor element was calculated for the pixels. The interaction fields and its standard deviation was calculated for all possible random distributions of 24 pixels around the test pixel. The measured and calculated interaction fields for different configurations are in good agreement. The results are applicable to very high density recording based on discrete particles.

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