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Simulations of the magnetization reversal of clustered Co–Cr particles

M. van Kooten [a], S. de Haan [a], J.C. Lodder [a], A. Lyberatos [b], R.W. Chantrell [b] and J.J. Miles [c]

[a] *MESA Research Institute, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands*
[b] *Department of Physics, University of Keele, Keele, Staffs ST5 5BG, UK*
[c] *Department of Electrical Engineering, University of Manchester, Dover Street, Manchester M13 9PL, UK*

Micromagnetic simulations of the magnetization reversal of clusters of 9 and 25 magnetostatically coupled Co–Cr particles are presented. The magnetostatic interaction between neighbouring particles facilitates reversal. The non-uniform magnetization configuration plays an important role in this effect.

1. Introduction

Co–Cr is a promising candidate for high-density magnetic recording. Under appropriate deposition conditions, Co–Cr has a columnar structure will a *c*-axis texture resulting in an effective perpendicular anisotropy. Films are made in a thickness range 100–500 nm and the cone-shaped columns have diameters at the surface of 30–100 nm [1]. On average, films contain about 20 at% Cr, but depending on the preparation conditions, compositional separation of Co and Cr can take place [2]. Cr can accumulate in the column boundaries which can lead to a partial exchange decoupling of the columns, or Cr can accumulate in some complicated pattern inside the column, which leads to complicated inhomogeneities in saturation magnetization and exchange stiffness. This can clearly have a strong influence on the reversal mechanism, and consequently on the recording performance.

The anomalous Hall-effect magnetometer (AHM) is used to measure hysteresis loops from an area of 200×200 nm of a Co–Cr film [3]. Simulations of a cluster of Co–Cr particles are useful in interpreting these measurements and obtain a better understanding of the reversal process in Co–Cr films.

In general, the magnetization reversal of elongated particles starts at both long ends by forming a vortex or a coherent structure, and proceeds towards the centre of the particle [4,5]. Simulations of continuous Co–Cr films were in good agreement with experiment [6]. For particulate Co–Cr films with uniform magnetization inside the particles, simulations showed a strong dependence of the coercivity on the exchange coupling between the grains. In the absence of exchange coupling, the coercive field was almost equal to the anisotropy field H_k, but the exchange coupling reduced this value to only 0.2 H_k, in agreement with experimental observations [7].

Correspondence to: M. van Kooten, Transducers and Material Sciences, University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands. Tel.: +31-53-893806/892751; telefax +31-53-309547.

2. Description of the model

The simulated clusters consist of particles in the shape of rectangular parallelepipeds that are subdivided into cubic elements with uniform magnetization. The energy density for each element i is

$$E_i = -k_{u1}\left(\hat{\boldsymbol{M}}_i \cdot \hat{\boldsymbol{k}}_i\right)^2 - \frac{A}{a^2}\hat{\boldsymbol{M}}_i \cdot \sum_{j=\delta i} \hat{\boldsymbol{M}}_j - \boldsymbol{M}_i \cdot \boldsymbol{B}_{\text{ext}} + \frac{\mu_0 M_s}{4\pi}\boldsymbol{M}_i \cdot \sum_j \left(\hat{\boldsymbol{M}}_j - 3\hat{\boldsymbol{r}}_{ij}\left(\hat{\boldsymbol{M}}_j \cdot \hat{\boldsymbol{r}}_{ij}\right)\right)\frac{a^3}{r_{ij}^3}, \quad (1)$$

where E_i is the total energy density, k_{u1} is the uniaxial crystalline anisotropy energy density, $\boldsymbol{k}$ is the anisotropy axis, A is the exchange stiffness, a is the element size, δi are the neighbouring elements of i, $\boldsymbol{B}_{\text{ext}}$ is the applied field, M_s is the saturation magnetization, and $\boldsymbol{r}_{ij}$ is the vector from element i to element j. The magnetostatic energy is calculated using a dipole approximation. This method overestimates the magnetostatic energy due to nearest neighbours. For the exchange energy, the finite difference approximation for the magnetization gradient has been used [5]. The equation of motion of the magnetization is given by the Landau–Lifschitz equation

$$\frac{\mathrm{d}\boldsymbol{M}_i}{\mathrm{d}t} = -\gamma \boldsymbol{M}_i \times \boldsymbol{B}_i - \frac{\alpha\gamma}{|\boldsymbol{M}_i|}\boldsymbol{M}_i \times (\boldsymbol{M}_i \times \boldsymbol{B}_i), \quad (2)$$

where γ is the gyromagnetic ratio, α is a phenomeno-

logical damping parameter, and $\boldsymbol{B}$ is the effective field $\delta E_i/\delta \boldsymbol{M}_i$. Equation (2) is evaluated using an analytical solution [6].

A hysteresis loop is simulated as follows. The applied field is decreased by small steps ΔH and the magnetization configuration is allowed to relax. The time step is chosen every iteration so that the maximum rotation of any moment will not exceed δ_{max}.

The calculation of the demagnetizing field is computationally efficient. The contribution of each element to the total demagnetizing field is only updated when the magnetization in that element has rotated by an angle larger than δ_0. A hierarchical method [8] is also used.

The computations were carried out on a Convex C240. One branch of the hysteresis loop of a 25-particle cluster (16200 elements) required 15 CPU hours.

3. Simulation results

The clusters of Co–Cr particles consist of 3×3 or 5×5 paralelepipeds of aspect ratio 1:3 and width 51.2 nm. The material parameters, obtained from torque and VSM measurements on thin Co–Cr films are $M_s = 400$ kA m^{-1}, $A = 1 \times 10^{-11}$ J m^{-1} and $K_{u1} = 1.6 \times 10^5$ J m^{-3}. The exchange length $l_{ex} = \sqrt{2A/\mu_0 M_s^2}$ is 10 nm and the anisotropy field $H_k = 637$ k Am^{-1}. The size of elements a was chosen sufficiently small (8.5 nm) for the resolution of the magnetization reversal in the cluster. The crystalline anisotropy axes of the particles are distributed randomly within a cone with a half top-angle of 0.03 rad about the film normal, as observed in Co–Cr films [1]. The cluster is surrounded by a continuous film, modelled as a uniformly magnetized medium with the average magnetization of the cluster.

It is expected that a many-body system has a complex energy surface. We therefore investigated the influence of the parameters ΔH, δ_{max} and δ_0 as described in section 2 on the hysteresis loop of the nine-particle cluster. Optimum results were obtained using $\delta_0 = 10^{-4}$ rad, $\Delta H = 10^{-3} H_k$ and $\delta_{max} = 0.1$ rad.

The hysteresis loop of a cluster depends strongly on the easy axis distribution. This is illustrated in fig. 1, which shows two hysteresis loops of nine-particle clusters. The coercive field hardly depends on the easy axis distribution. The hysteresis loop of a 25-particle cluster shown in fig. 2 has a coercive field that is smaller, probably due to scale effects. The dotted line in the same figure shows the hysteresis loop that would be obtained if the interaction is just with the mean perpendicular field, using the switching field of an isolated particle of the same dimensions ($H_{sw} = 635$ kA m^{-1} [9]). The gradually decreasing slope of the simulated

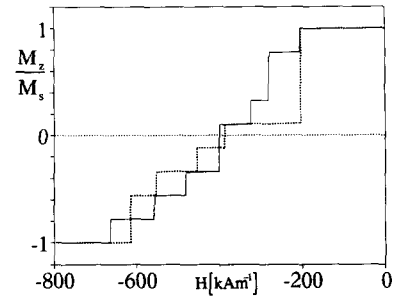

Fig. 1. Two hysteresis loops of nine-particle clusters of Co–Cr particles. The easy axis distribution is different for each loop.

loop when reversal proceeds can be clearly seen. The lower H_c indicates the presence of interaction effects other than via the mean demagnetizing field. This is possibly due to the presence of in-plane interaction fields as will be discussed later, since simulations of the angular dependence of isolated Co–Cr particles show a sharp decrease in the switching field at small field angles [9]. In rf-sputtered Co–Cr films with comparable thickness and column diameter, $H_c/H_k = 0.23$ [10], whereas $H_c/H_k = 0.63$ in the simulated case.

Typical equilibrium states are shown in fig. 3. A particle switches magnetically, only if there is a reversed neighbour. In the nine-particle cluster, this is not remarkable, but in the 25-particle cluster, there are many other candidates for switching, and consequently the observed correlation attains a greater significance. The cluster size is too small to distinguish between dot- or stripe-like domains. Both are observed in Co–Cr films [11]. Dot-like domains covering about four columns that grow to twice that size are observed in high-coercivity films; dot-like domains that stripe out are observed in low-coercivity films. The distinction between low- and high-coercivity fields is often interpreted in terms of interaction strength (strong or weak)

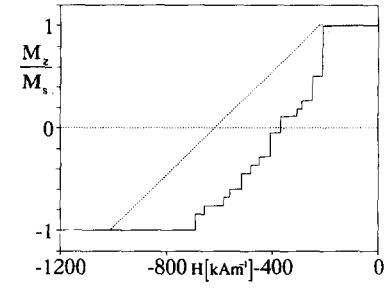

Fig. 2. Hysteresis loop of the 25-particle cluster of Co–Cr particles (solid line) and the theoretical loop in the case of only perpendicular demagnetizing fields (dotted line).

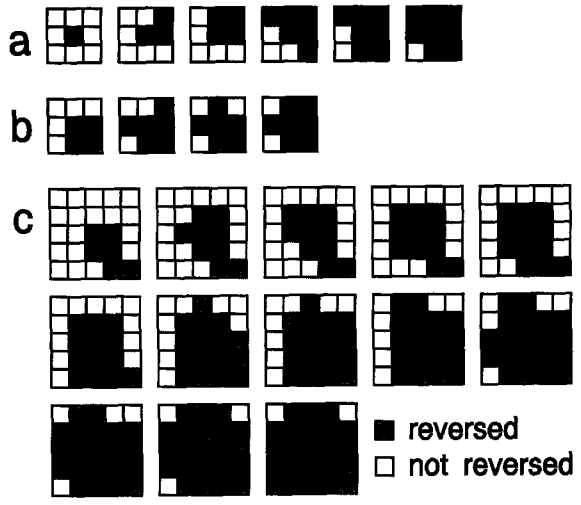

Fig. 3. Equilibrium configuration (top view) of the nine-particle clusters (a and b) and of the 25-particle cluster (c) of Co–Cr particles at various stages of reversal.

of the columns. The low-coercivity films have hysteresis loops with a high slope of the hysteresis loop at the onset of reversal (shoulder) because the wall coercivity is lower than the nucleation field. This appears to be similar to the observed behaviour in our simulations, but the origin of the shoulder in fig. 2 is different. Using a simplified model for the cluster, where each column was represented by a single domain particle with just two states (magnetization up or down) and an assigned switching field, a good fit to the hysteresis loop of fig. 2 was obtained on the assumption that a reversed column has a positive influence on the reversal of its neighbours. The model will be described in detail in a separate publication.

The collective reversals (figs. 2 and 3, more than one particle switching at the same field) can be understood in terms of strong in-plane interaction fields and the resulting facilitating effect on the switching of neighbouring particles during the reversal of a particle. The existence of dot-like domains covering more then one column in Co–Cr films is probably evidence for the existence of collective reversal.

In more detail, the magnetization configuration of two particles of a nine-particle cluster just before reversal is shown in fig. 4. The bending of the magnetization at the interface of particles with opposing magnetization can be clearly seen. This indicates that strong in-plane interaction fields are present.

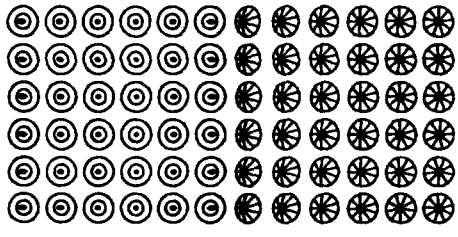

Fig. 4. Detailed magnetization configuration (top view, one umbrella is one element) in two particles, one of which is reversed, at the surface of the nine-particle cluster of Co–Cr particles.

4. Conclusions and discussion

Both the coercive field (which is much lower than the switching field of an isolated particle) and the switching order leads to the conclusion that the magnetostatic interaction between neighbouring particles facilitates reversal. The strong bending of the magnetization at the surface and the collective reversals indicates that the in-plane components of the interaction field play an important role in this interaction.

The coercivity in the Co–Cr model presented is still rather high. Since the coercivity only decreases by a small amount when the system is enlarged from nine to 25 particles, this high value is not attributed to the small size of the clusters. Two other possible origins are the chosen model for the particles and the exchange interaction. The particle model could be refined by introducing inhomogeneities in the saturation magnetization, the exchange stiffness and the crystalline anisotropy and by assuming a more realistic shape, where irregularities in the shape play probably a more important role than, for example, the difference between hexagonal or rectangular shape. To introduce an exchange interaction between the particles, a larger sample is needed: initial simulations with a small exchange coupling have shown that the particles reverse magnetically simultaneously.

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