Magnetization processes in Co–Cr submicron samples: Hall measurements and micromagnetic simulations

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The magnetization reversal of Co–Cr with perpendicular anisotropy is studied by anomalous Hall effect measurements and by micromagnetic simulations. In a measured hysteresis loop of a 300 nm×300 nm sample (consisting of approximately 40 columns of Co–Cr), discrete jumps are observed, together with a more or less continuous change in magnetization, the latter with both positive and negative sign. The continuous and discrete parts of the hysteresis loop are separated to extract micromagnetic information from the anomalous Hall measurement. The discrete jumps are attributed to parts of columns that switch irreversibly, the continuous magnetization change is attributed to reversible rotation, partly of volumes with in-plane anisotropy. These assumptions are checked by means of a micromagnetic model.

I. INTRODUCTION

The magnetization reversal mechanism of Co–Cr for perpendicular recording is still not entirely understood. Neither domain wall motion nor incoherent reversal are able to explain the behavior, especially for the high coercivity films. Anomalous Hall effect measurements are applied on Co–Cr. With suitable lithography and etching, the measurement area can be as small as (300 nm)².¹ With this technique, the reversal can be clarified up to a great extent. For this purpose, we used the step size distribution in the measured hysteresis loop.¹ To interpret the measured hysteresis loops, simulations are necessary to check whether intuitive models are correct or need extension. Micromagnetic simulations are believed to be most suitable for this task, because they start with first principles (exchange, magnetization, anisotropy, and morphology) and yield hysteresis loops and magnetization patterns. The morphology, the texture, and the composition are incorporated into the model by varying the exchange, the magnetization, and the anisotropy locally.

II. ANOMALOUS HALL MEASUREMENTS

A Co–Cr sample with a Cr content of 23 at. % is sputtered on Si covered with thin layer of SiO₂. The unetched sample has an M_s of 321 kA/m and a perpendicular coercivity H_c of 93 kA/m. The film thickness is 200 nm and the average column size at the surface is 60 nm. The samples are etched to a Hall cross geometry with a central area of (300 nm)².² The measurement area contains approximately 40 columns. At least 70% of the contribution to the Hall voltage comes from the central area of the sample of (300 nm)².³

In the anomalous Hall effect measurement setup, a current is sent through the sample, and the voltage perpendicular to the current, is measured. The hysteresis loop of an etched sample is shown in Fig. 1.¹ The loop shows many more large discrete magnetization changes (steps) as there are columns and a more or less continuous magnetization change between the steps. Further, changes with a negative ΔM can be seen. Five steps corresponding to the switching of one column are found, but most steps are smaller than 2% of M_s , corresponding to less than half a column. The

Johnson noise of the sample is the main source of noise and is estimated to correspond with $0.001M_s$ in the Hall loop. This threshold is indicated in Fig. 1.

The measured hysteresis loops are decomposed as follows: The changes in magnetization ΔM after each field step (see Fig. 1) are categorized into five different classes:

- I. $\Delta M > 0.003M_s$ [equivalent to $> (30 \text{ nm})^3$];
- II. $0.003M_s > \Delta M > 0.001M_s$;
- III. $0.001M_s > \Delta M > 0$;
- IV. $0 > \Delta M > -0.001M_s$; and V. $-0.001M_s > \Delta M$.

The steps of the different classes are put together to a hysteresis loop again (see Fig. 2 for a clarification of the method). Since one extracted hysteresis loop consists only of magnetization changes of one class, we will call these loops Stepsize-distinguished Partial Hysteresis loops (SPH). The superposition of the SPHs from class (I), (II), and (III) yield a loop with a “saturation magnetization” of $1.3M_s$.

The Hall loop, together with the SPHs, are shown in Fig. 3. The shapes of the SPHs are very different. Loop I in Fig.

FIG. 1. The hysteresis loop of the etched sample³ with the definition of ΔM for both the descending and the ascending branch. Inset: enlarged part of the loop with clearly visible steps and the thresholds (see the text).

FIG. 2. Example of the extraction of two step size-distinguished partial hysteresis loops (SPHs). Changes smaller than the discrimination level (upper curve) and changes larger than the discrimination level (lower curve) are separated.

3(a), consisting of ΔM s from class I, is an almost ideal hysteresis loop of a particulate medium with perpendicular anisotropy. The loop shows the usual shearing due to demagnetization, a sharp onset of magnetization reversal, and only a small "tail," a decrease of the slope at the end of magnetization reversal. The coercivity is 10% higher than the coercivity of the original hysteresis loop. Loop II, consisting of ΔM s from class II, is clearly different. It shows a gradual onset of magnetization reversal, no tail, and a coercivity that is about half of the film coercivity. The loop consisting of negative changes above the noise level [V in Fig. 3(b)] has the same properties as loop II, except for the lower saturation value. The loops consisting of magnetization changes below the noise level (III and IV) show hysteresis and saturation. We tend to attribute this, at least partly, to magnetization reversal.

The number of magnetization changes of class I is 155, much larger than the number of columns in the measurement area. This indicates that the column is not the smallest magnetic unit in this particular Co-Cr film. A microstructure that could explain this is the CP structure,⁴ where small Co-rich platelets are embedded in a Cr-rich matrix inside the column. The small changes can be explained by reversible rotation of regions with in-plane anisotropy,⁵ which have no perpendicular anisotropy. The negative ΔM s might indicate the presence of magnetic volumes at the limit of superparamagnetism. According to the step size, their volume could be around $(20 \text{ nm})^3$. When using the Néel-Arrhenius law for time decay in particle assemblies $1/\tau = 10^{-9} \exp(K_1 V/kT)$ ⁶ the estimated superparamagnetic limit of Co-Cr is $(8 \text{ nm})^3$ when using a relaxation time τ of 100 s and an anisotropy constant K_1 of $1.6 \times 10^5 \text{ J/m}^3$. For particulate media, it is also observed that the mentioned formula does predict the so-called activation volume, which is much smaller than the particle volume.⁷ The magnitude of the SPH of class V can be an indication for the volume fraction of magnetic units at the superparamagnetic limit. With a micromagnetic model,

FIG. 3. The original Hall loop and the various step size-distinguished partial hysteresis loops (SPHs).

the influence of some microstructural parameters on the observed magnetic behavior are investigated.

III. MICROMAGNETIC SIMULATIONS

The used micromagnetic model⁸ consists of particles in the shape of cubes of $(50 \text{ nm})^3$, which are subdivided into cubic elements of $(5 \text{ nm})^3$ with uniform magnetization. Exchange between the particles is modeled by assigning an exchange to a few randomly chosen element pairs, which are on the particle boundaries. The initial layer, as present in our Co-Cr, is modeled by assigning an in-plane easy axis to cubes of eight elements on the bottom two rows of elements in the model. These cubes are exchange coupled to the particle to which they belong.

A typical simulated hysteresis loop of a 25 particle cluster with the SPH containing magnetization changes smaller than $0.003 M_s$ is shown in Fig. 4. These changes are due to reversible magnetization rotation. Like in the measurement, the coercivity of the SPH is about half the coercivity of the

FIG. 4. A typical simulated hysteresis loop and the SPH containing the reversible rotation. The volume with in-plane anisotropy is 2%, the exchange coupling between the particles is 20%, and the spread of the easy axes of the particles is 7°.

whole system. Immediately observable and comparable quantities of the simulations are the coercivity of the major loop H_c , the coercivity of the SPH $H_{c,rev}$, and the contribution of the SPH to the total hysteresis loop M_{rev} , which are indicated in Fig. 4.

A moderate spread of the easy axes of the particles (up to 15°) only influence H_c , $H_{c,rev}$, and M_s by a few percent. The initial layer volume affects, as expected, M_{rev} considerably (Fig. 5). On the basis of this quantity, an estimate of the total volume with in-plane anisotropy can be made. In Fig. 5, H_c and $H_{c,rev}$ are shown as a function of the initial layer volume. The sharp decrease of H_c with increasing initial layer volume can partly be attributed to the artificially high switching field of micromagnetically modeled particles (Brown's paradox⁹), the reversal of the initial layer facilitates nucleation of particle reversal. $H_{c,rev}$ can, like M_{rev} , be used to estimate the volume fraction of the initial layer of the investigated Co-Cr sample, since reversible rotation in the regions with perpendicular anisotropy yields a $H_{c,rev}$ almost equal to H_c , as can be concluded from the simulation with no initial layer. With increasing initial layer volume, $H_{c,rev}$ decreases rapidly. Simulations show further, in agreement with Ref. 10, that exchange interaction between the particles lowers H_c considerably (20% exchange lowers H_c by 25%). Exchange interaction does not affect $H_{c,rev}$ and M_{rev} .

IV. CONCLUSIONS

We showed that the analysis of hysteresis loops of sub-micron Co-Cr samples on the basis of the measured magnetization changes yields information on distinguishable mag-

FIG. 5. The magnitude of the SPH (M_{rev}) and the coercivities of the original loops (H_c) and of the SPH ($H_{c,rev}$) as a function of the volume fraction of the initial layer.

netic volumes in the sample. The size of the measured discrete magnetization changes shows that the average magnetic unit in Co-Cr is considerably smaller than one column. We observed five steps of approximately one column, the rest of the steps is smaller. From the presence of negative ΔM s and their distribution along the hysteresis loop, we conclude that magnetic units on the limit of superparamagnetism could be present in Co-Cr. Magnetic viscosity measurements and temperature-dependent hysteresis measurements will have to give more information about this.

Simulations show that the initial layer has a large effect on the magnetization processes in the film. Its magnetization process is reversible rotation. Simulations show further that the exchange coupling of the initial layer with the columns facilitates their magnetic reversal.

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- ¹ S. de Haan *et al.* (to be published).
- ² S. de Haan, J. C. Lodder, and Th. J. A. Popma, *J. Magn. Soc. Jpn.* **15**, 349 (1991).
- ³ B. C. Webb and S. Schultz, *IEEE Trans. Magn.* **24**, 3006 (1988).
- ⁴ Y. Maeda and M. Asahi, *J. Appl. Phys.* **61**, 1972 (1987).
- ⁵ J. C. Lodder, T. Wielinga, and J. Worst, *Thin Solid Films* **101**, 61 (1982).
- ⁶ L. Néel, *Adv. Phys.* **4**, 191 (1955).
- ⁷ A. M. de Witte, K. O'Grady, G. N. Coverdale, and R. W. Chantrell, *J. Magn. Magn. Mat.* **88**, 183 (1990).
- ⁸ M. van Kooten, S. de Haan, J. C. Lodder, A. Lyberatos, R. W. Chantrell, and J. J. Miles, *J. Magn. Magn. Mat.* **120**, 145 (1993).
- ⁹ W. F. Brown, Jr., *Rev. Mod. Phys.* **17**, 15 (1945).
- ¹⁰ J.-G. Zhu and H. N. Bertram, *J. Appl. Phys.* **66**, 1291 (1988).