Magnetic Microstructures of Perpendicular Magnetic-Recording Media

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Introduction

Magnetic recording has been the dominant recording technology for information storage since the invention of the computer. Currently, 1-Gbit/in.² longitudinal magnetic recording (LMR) systems^{1,2} have been realized and densities of 10 Gbit/in.², having bit areas less than 0.1 μm^2 , are being developed.³ To reach this goal, a drastic scaling down of the track pitch, bit-cell length, head gap, medium thickness, and head-medium spacing is required. If this trend of increasing densities continues, an areal density of more than 300 Gbit/in.² is predicted in the 21st century,⁴ based on computer simulation⁵ using the perpendicular magnetic recording (PMR) mode instead of the current LMR scheme. Magnetic-recording technologies and related materials have already been discussed in another issue of the *MRS Bulletin*,⁶ and hence in this paper, we concentrate on Co-Cr-X material used as a medium for PMR.

The PMR mode has been studied since 1975⁷ and at present, Co-Cr-X (e.g., X = Ta) films with perpendicular anisotropy are the most promising media material. In general, such media should have the following properties: easy axis of magnetization perpendicular to the film plane, suitable coercivity (H_c) and remanent magnetization (M_r) for storing the information and reading it at a high signal-to-noise (S/N) level, uniform columnar size with a small diameter, magnetically uncoupled columns having a magnetization reversal based on rotation

instead of a domain-wall motion, chemical stability under various environmental conditions, and a small surface roughness. In order to achieve the desired magnetic anisotropy and coercivity, a columnar morphology (small diameter) with an hcp [0001] texture and exchange-decoupled, columnar boundaries—to create a magnetic microstructure for single domain switching columns with high coercivity—should be obtained. An overview of the preparation, microstructure, and magnetic properties of Co-Cr thin films is given in Reference 8. Depending on the deposition parameters, a so-called initial layer (with an in-plane magnetization) can be present.

To obtain high coercivity, the grains are magnetically isolated with a nonferromagnetic Co-Cr composition (at% Cr > 26) by compositional separation. In addition to appearing in the columnar boundaries, compositional separation can also be found in the column itself,⁹ the so-called chrysanthemum-like pattern (CP). The main features of the CP structure are Co- and Cr-rich stripes, with spatial periodicity of 3–7 nm, perpendicular to the column boundaries. Results obtained by atom-probe field-ion microscopy (APFIM) have shown how the concentration fluctuations in the grains (columns) are distributed.¹⁰ Over a distance of 40 nm in the planar direction of a Co-Cr column, differences of 30 at% Cr and 7 at% Cr have been measured. The latter composition is ferro-

magnetic while the composition above 26 at% Cr is paramagnetic. The results obtained by compositional separation studies support the anomalous Hall effect measurements (see later) obtained on our samples.

The magnetic structures (magnetic domains and written bits) in Co-Cr films are strongly related to the microstructure, morphology, and compositional separation. A simple schematic structure (see Figure 1) of sputtered Co-Cr films consisting of equal-size columns is used as a model to discuss the possible magnetization-reversal phenomena. Figure 1a shows the microstructure with equal columnar size and shape, and a columnar boundary. In this case, the interaction between the columns occurs by exchange and magnetostatic interactions. The boundary can only hinder the movement of the domain wall, which means, in principle, an increase in H_c . For higher H_c 's, we need to break up the exchange forces between the columns. This can be realized by compositional separation or separation (by voids) of the columns, which has been also shown in the case of Co-Cr-X media for LMR. In the case of compositional separation, a nonferromagnetic Cr-rich composition is present between the columns (Figure 1b). The more complicated CP structure of one column in combination with a Cr-enriched column boundary is shown in Figure 1c. These complicated structures have many consequences for the switching behavior of the magnetization and, moreover, for the coercivity. The reversal of the magnetization depends on the exchange and magnetostatic interactions between the columns or cluster of columns. For a reasonable S/N , it is necessary to have at least 100–200 of these magnetic entities in a bit. Smaller bit sizes consequently need smaller individual switching units. In order to understand the magnetization reversal in a small bit (e.g., 10 Gbits/in.²), the question arises whether the hysteresis loop [measured with a vibrating sample magnetometer (VSM)] is still the most relevant magnetic characterization for understanding reversals on this scale. New approaches are necessary to bridge the gap between micro- and macroscopic behavior.

Macro-Meso-Micro Magnetic Properties

To understand the relation between the *macro*magnetic properties (e.g., hysteresis-loop properties such as M_s , M_r , H_c measured with a vibrating sample magnetometer), *micro*magnetic

properties (obtained by simulation and calculation), and *mesoscopic* properties [obtained by experimental methods such as Lorentz microscopy, magnetic force microscopy (MFM), and anomalous Hall measurements (AHM)], it must be realized that these properties are operating at a variety of length scales. Starting at the atomic level, the interaction phenomena between spins and orbit, magnetic exchange interactions, and dipole-dipole interactions must be considered (micro-

magnetic behavior). Moreover, the thin-film media discussed here are composed of small crystallites consisting of a three-dimensional periodic arrangement of (magnetic) atoms (mesoscopic behavior). In the simplest case, each magnetic atom has the same local environment in which the neighboring atoms (magnetic or otherwise) form a spatial configuration of a particular symmetry. A typical thin-film medium for high-density recording consists of individual magnetic crystals. When a VSM hysteresis loop from a typical sample (e.g., $5 \times 5 \text{ mm}^2$) is measured, a hysteresis curve of 15,000 interacting crystals is obtained assuming a size of 40 nm. If a typical bit size for such media is about $3 \mu\text{m}^2$, the recorded information is obtained from 2,500 crystals. The micromagnetic calculations are mostly obtained from 20–100 of such crystals because of the computer capacity and the reasonable calculating time.

Consequently, there is a gap between micromagnetic simulations and the macromagnetic properties obtained by experimental methods (e.g., hysteresis loop). Therefore, it is necessary to develop experimental methods from which magnetic and microstructural information from similar volumes can be obtained. Only then is it possible to find a more definitive relation between the microstructure, local chemical composition, and magnetic behavior on a length scale more related to high-density recording. Given 10 Gbits/in.² (expected in the year 2000), the fundamental structural dimensions (crystal size and surface topology), intrinsic magnetic structures (domains), and bit dimensions are all approaching similar sizes. Research was started in our laboratory in three complementary areas: (1) investigation into the relation between shape and magnetic behavior in artificially etched "bits," (2) measurement and micromagnetic modeling of the switching behavior of individual magnetic entities in submicron Hall crosses,^{5,11} and (3) observation of microstructure and written bits by AFM and MFM.¹² These mesoscopic measurements serve as input for micromagnetic simulations.¹³

Anomalous Hall Effect Measurements

In order to study the reversal mechanism in more detail, the hysteresis loop of submicron dimensions for Co-Cr samples was determined with the so-called anomalous Hall effect (AHE).¹¹ Various Co-Cr samples were measured. For this purpose, a series of small, cross-shaped Hall structures were prepared by

Figure 2. An AHE hysteresis loop (bottom) of a 300-nm² etched Co-Cr structure with an enlargement of a small area of the loop (top) in the field range of 170–190 kA/m. Also, the AHE voltage of one homogeneous Co-Cr column is indicated, as well as the noise level.

electron-beam lithography and ion-beam etching. The smallest structure was $0.2 \times 0.2 \mu\text{m}^2$. A measured AHE hysteresis loop (Figure 2) of $300 \times 300 \text{ nm}$ consists of about 40 columns. Discrete jumps in the loop can be seen in combination with a continuous change in magnetization. The discrete parts of the hysteresis loop are due to the irreversible parts of the columns. The continuous M change (30% of the total volume) originates from the reversible rotation. It was concluded from the analysis of the hysteresis curve that the reversal of the measured Co-Cr is a mixture of the magnetization rotation and domain nucleation in the soft magnetic initial layer. This has been further used for micromagnetic simulations.¹³ By recording AHE loops of these samples, the reversal can be clarified to a great extent. For this

Figure 1. Model of Co-Cr sputtered perpendicular magnetic recording (PMR) medium in which the morphology is determined by the type of compositional separation. (a) The ideal columnar morphology. (b) Compositional separation in the columns (CP structure) as well as at the boundaries. (c) Compositional separation only on the column boundaries.

purpose, we used the step-size distribution of the magnetization (ΔM) in the AHE loop. To interpret the results, simulations are necessary to check whether intuitive models are correct or need extension. The number of magnetization changes is much larger (about a factor of 4–6) than the number of columns in the measured sample. 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. The small changes can be explained by reversible rotation of regions with in-plane anisotropy,¹⁴ which have no perpendicular anisotropy. From the measured AHE loop, we also found negative ΔM values. This might indicate the presence of magnetic volumes at the limit of superparamagnetism. According to the step size, their volume might be around 20 nm³. With a micromagnetic model, the influence of some microstructural parameters on the observed magnetic behavior has been investigated. The results obtained by compositional separation studies and AHE measurements support each other. In micromagnetic simulation, the compositional separation is incorporated and with this addition, the AHE results can be calculated and are qualitatively in agreement with the measured results.¹³

Micromagnetic Simulations

Micromagnetic simulations are believed to be most suitable for understanding the magnetization process on a micromagnetic level because they start with basic principles (exchange, magnetization, anisotropy, and morphology) and yield hysteresis loops and magnetization patterns. The morphology, texture, and composition are incorporated into the model by varying the exchange, magnetization, and anisotropy locally. The micromagnetic model¹³ used consists of particles (Co-Cr columns) in the shape of cubes of (50 nm)³, which are subdivided into cubic elements of (5 nm)³ with uniform magnetization (see top of Figure 3). Exchange between the particles is modeled by assigning an exchange to a few randomly chosen element pairs that are on the particle boundaries. The initial growth layer, as present in our Co-Cr, is modeled by assigning an in-plane easy axis to cubes of eight elements in the bottom two rows of elements in the model. These cubes are exchange-coupled to the particle to which they belong. This partly overcomes the well-known problem of a too high H_c/H_k (anisotropy field) in micromagnetic simulations¹⁵ since it reduces

Figure 3. The model structure of 25 Co-Cr columns for micromagnetic simulation. Each column consists of small elements (cubes). The columns have been modified in Co-rich and Cr-rich areas (black and white, respectively) and also an initial layer with an in-plane anisotropy is situated at the bottom of the columns (gray).

the coercivity by more than 30%. Further reduction of the coercivity can be obtained by assuming that small regions have a higher crystal-anisotropy constant (K_1) and/or a lower M_s , such that saturation of the entire film is not saturated below reasonable fields used in a measurement setup. Because the AHE measurements prove that the average

magnetic-unit size is not equal to the column size, each column is modeled as a Co-poor matrix with three Co-rich platelets. Although the parameters used are not completely equal to the dimensions and distribution of the compositional separation, they show reasonable agreement with the experimental AHE loop (see bottom of Figure 3).

Magnetic Force Microscopy

The principle of the MFM used is described in Reference 16, and it is usually operated in the dynamic scan mode. Due to the interactions of the magnetic tip with the stray fields above the surface of the sample, the effective spring constant of the cantilever is changed, leading to a shift in its resonance frequency. The images obtained from the MFM are composed from the gradient of the force that varies as a function of the stray field above the sample. The measured stray-field distributions are only indirectly related to the magnetization in the sample. An attractive force (on the cantilever) can be represented as white and the repulsive force as black in the final image. This type of image is interpreted as the two opposite directions of magnetization in the sample and finally can be interpreted as the magnetic structures (domain structure). The most important part of the MFM is the performance of the magnetic tip. Special fabricated tips have been used showing a single-pole tip behavior in all practical measurements so far, and the resolution for measuring magnetic details is better than 30 nm.¹² The photograph of Figure 4a shows written bits (200 kilo flux reversals per inch [kfrpi]) in a 400-nm-wide track in a medium for PMR. Here the Co-Cr-Ta layer has a thickness of 70 nm, and it was grown on a very thick (7- μm) Ni-Fe underlayer.¹⁷ The magnetic structure next to the track is about 150 nm. The linear-bit size of 200 kfrpi is about 127 nm and represents an area density of 12 Gbit/in.². Here we see that the written bit size is smaller than the size of the magnetic structures. This may have many consequences for bit stability and medium noise. Moreover, it can be seen that the side border of the track is not straight, which may be due to the fact that some bits are connected to the magnetic structures outside the track. By SEM and AFM, the surface topology was also measured (Figure 4b). From this, we measured an average columnar/crystal diameter (at the surface) of about 45 nm. The bit size of the 200-kfrpi bit (area of approximately 0.05 μm^2) is indicated in the AFM surface picture. It can be seen that only about 30 crystals are covering the area. The number of crystals here is too low for a reasonable noise level. For obtaining good noise characteristics with this density, the crystal size should decrease to about 20 nm in diameter so that a sufficient number of crystals can contribute to the statistical noise. Increasing the density means smaller bit areas and, again, a decrease in crystal di-

Figure 4. MFM observation (a) of a perpendicular Co-Cr medium consisting of a 400-nm track width and a linear density of 200 kfrpi (bit length $\approx$ 130 nm). (b) From the same surface, the bit area is shown (400 $\times$ 130 nm²) in the AFM image.

ameter is necessary. For 100 Gbit/in.², the bit area must decrease by more than a factor of eight. Assuming the same track width of 400 nm, the bit length should be 15 nm. A crystal diameter of about 7 nm is necessary.

Conclusions

The PMR mode can reach extremely high densities and will be an important competitor for LMR mode especially in the extreme high-density applications. It has, in principle, sharp transitions and not the critical limitations of the film thickness in the high-density area, as is needed for LMR. Compositional separation divides the Co-Cr crystals/columns into smaller ferromagnetic structures than the columnar dimensions. Anomalous Hall measurements showed that the analysis of hysteresis loops of submicron Co-Cr samples on the basis of the mea-

sured magnetization changes yields information on magnetic volumes that can be distinguished 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. A density of 12 Gbit/in.² for a PMR hard disk has been observed and indicates that there is an interaction between the magnetization fluctuations beside the track and the written bit. The magnetization fluctuations measured with MFM are related to clusters of Co-Cr columns. The magnetic structures measured are always larger than the average columnar diameter. To obtain sharp tracks, the size of the intrinsic magnetic structures beside the track should be smaller than the linear-bit length. The microstructure and morphology are very important for the new class of high-density recording media. Magnetic properties to be optimized are the coercivity, remanence, film thickness, and columnar size and shape. The sharpness and shape of the written transition are determined by the grain morphology and the magnetic coupling of the texture of the grains. The particular behavior will be ultimately limited by the superparamagnetism. With respect to perpendicular recording, high linear-bit densities have been demonstrated on laboratory scale, achieved by recording a medium consisting of Co-Cr-Ta on a soft magnetic underlayer with a special single-pole head. The ultimate density of a bit area (2,500 nm²) is predicted with bit lengths smaller than 50 nm.

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