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Invited Review

Magnetic structures in Co–Cr media for perpendicular magnetic recording

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Abstract

High bit densities have been demonstrated in longitudinal as well as in perpendicular magnetic recording. For the latter an area density of more than 12 Gbit/in² has been obtained in a sputtered Co–Cr–Ta hard disk with a soft magnetic underlayer recorded with a special single pole head. In this paper the role of microstructure and morphology in relation to the compositional separation is discussed. Very sensitive anomalous Hall measurements have been performed from submicron Co–Cr samples to obtain more detail information about the reversal characteristics of the material. The results obtained have been used in our model for micromagnetic simulations. One of the conclusions is that most of the magnetic entities reversing their magnetisations are much smaller than the volume of one Co–Cr column.

Keywords: Co–Cr; Magnetization reversal; Magnetic structures; Coercivity; AHE measurements; Micromagnetism; MFM

1. Introduction

Magnetic recording has been the dominant recording technology for information storage since the invention of the computer. The demand from the user is for more compact information carriers. Smaller formats are useful and can be produced more cheaply. For such developments knowledge and expertise of the many relevant subjects is needed like the mechanics of the recording system, the intelligent electronic system, development of new materials and designs for heads and media and a better knowledge of the interface between head and

medium. The combined approaches of all the research have led to the realisation of the 1 Gbit/inch² longitudinal magnetic recording (LMR) systems [1,2]. Since 1992, the 10 Gbit/in² longitudinal recording, having bit areas less than 0.1 μm^2 , has been discussed [3]. To reach this goal drastic scaling-down of the track pitch, bit-cell length, head gap, medium thickness and head–medium spacing have been made. Beside many other aspects the availability of sputtered thin-film media was essential in this development. Based on the trend of increasing densities an area density of more than 300 Gbit/in² will be available in the 21st century as predicted in [4]. This statement was based on computer simulation [5] using the perpendicular recording mode (PMR) instead of the current LMR. Because the concept of the magnetic recording technologies and related materi-

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Fig. 1. An isolated recorded track with written bits for LMR (a) and PMR (b) in a medium having a thickness (δ) and a track-width (tw), recorded wavelength (λ), linear bit-length (bl), recorded transition and bit-cell area.

als for LMR are already extensively discussed in many reference books [6] in this paper we concentrate on the behaviour of Co–Cr–X material used as a medium for PMR.

1.1. Magnetic recording modes: LMR vs. PMR

In Fig. 1 one track with written bits are given for the two (LMR and PMR) modes of magnetic recording. In both cases the area density is given by the product of the linear bit density and the track density. Higher density means creating narrower tracks and more compact bits. Transition shape and length are extremely important for the recording performance [6]. For LMR the magnetization vector forms a head-on state of transition which results, for thin film media in a saw-tooth shaped transition. Medium noise, mainly originating from the transition becomes larger at higher densities [7]. In the case of PMR the antiparallel magnetization in the adjacent bits are responsible for a significant reduction of the

demagnetising field especially at higher densities. The medium noise mechanism is very low in the case of high densities [7]. After searching the published results in the literature one can find that the ratio (bit length)/(medium thickness) (bl/δ) for Co–Cr–(X) thin film media in LMR is about 10–20 and for PMR about $1/3$ – $1/5$. From this data one can conclude that media having a perpendicular anisotropy can be made with larger layer thicknesses which are favourable for higher densities (higher signal, easier preparation conditions and smaller crystal size in relation to the critical volume for superparamagnetic behaviour as will be shown later). To obtain smaller transitions in the LMR mode the $M_r\delta$ should be small and the H_c high. This means very thin medium thickness (δ), high M_r to obtain sufficient signal and a magnetic microstructure consisting of single domain particles (SDP) to create a high coercivity (H_c). Moreover the stringent magnetic requirements on media noise for the advanced high density longitudinal media for the next decade will be met by the use of quaternary and five-element alloys in either single layer or laminated configurations. Recently various schemes for the design of multilayered media have been discussed [8] and for tailoring all the properties such as texture, anisotropy, in-plane H_c and noise performance one can come to an optimised structure which consists of about 9 different layers including the lubricant, overcoat and overlayers. Although PMR is not commercially available today may be it could be a reasonable alternative for the future super density recording system. Due to the total amount of research activities and the published results (e.g. Ref. [9]) there are no specific scientific problems preventing the use of this recording mode. Nevertheless, in spite of lack of commercial success the perpendicular mode has stimulated the developments in LMR and, of course, presents many new scientific questions that have to be resolved concerning new specific heads, contact between head and medium and, last but not least, the development of suitable thin-film media.

Therefore it is very interesting to study theoretically and experimentally the similarities and differences for the two recording modes. In the author's laboratory special attention is paid to the reversal behaviour of media for PMR. An overview of the results obtained is given in this paper.

2. Microstructural aspects and magnetic behaviour of PMR media

The PMR mode has been studied since 1975 by discussing the circular magnetisation mode and the technology for preparing a Co–Cr film with a perpendicular anisotropy [10]. At present Co–Cr–(X) (e.g. X = Ta) has been the most promising media material. Suitable Co–Cr media with perpendicular anisotropy have been made mostly by sputtering. In general it should have the following properties: easy axis of magnetisation perpendicular to the film plane; suitable coercivity (H_c) and remanent magnetisation (M_r) for storing the information and reading it at a high S/N level, and uniform columnar size with small diameter; magnetically uncoupled columns having a magnetisation reversal based on rotation instead of domain-wall motion; chemical stability under various environmental conditions with a small surface roughness.

In order to realise the magnetic anisotropy and the coercivity a special microstructure should be ob-

tained, namely 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. An overview of the preparation, microstructure and magnetic properties of Co–Cr thin films is given in [11]. Depending on the deposition parameters a so-called initial layer (with an in-plane magnetization) can be present.

2.1. Compositional separation

To obtain high coercivity the grains are magnetically isolated with a non-ferromagnetic Co–Cr composition (at% Cr > 26) by compositional separation (CS). Beside the columnar boundaries CS can also be found in the column itself. Maeda [12] first introduced the so-called chrysanthemum-like pattern (CP). Fig. 2 shows a TEM observation of a typical CS microstructure with CP patterns revealed by chemical etching. The white stripes within each crystal are thought to correspond to dissolved highly Co-rich regions and the dark areas correspond to passivated Cr-enriched regions. Consequently, this observation shows Co and Cr-rich regions in one crystal which means that the film consists of ferromagnetic regions smaller than one column. The main features of the CP structure are Co-rich stripes that tend to be perpendicular to the column boundaries. The Co and the Cr-rich components are strongly influencing the magnetic properties. The spatial periodicity of CS in sputtered Co–Cr layers on top of soft magnetic Ni–Fe layers is in the range of 3–7 nm [13]. There are many different possible explanations of such a CS structure (which has never been observed in Co–Cr bulk alloys) in the literature [14–22]. Most consistent work in this field has been published in Refs. [23–27]. Results obtained by APFIM (Atom Probe Field Ion Microscope) have shown how the concentration fluctuations in the grains (columns) are distributed [21,28,29]. 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 ferromagnetic while the composition above 26 at% Cr is paramagnetic. The fluctuations are less than 10 nm. The results obtained by CS studies support the anomalous Hall effect measurements (see later) obtained on our samples.

Fig. 2. TEM observation of a selectively etched Co–Cr sample showing CS structures with a CP pattern (Courtesy Dr Maeda, NTT Basic Research Laboratory, Japan).

2.2. Magnetic structures and reversal mechanism

The reversal of the magnetization is a basic principle of magnetic recording. Magnetization in a material can be reversed by applying a large enough field following which the whole material will become saturated in a direction parallel to the field. The two different states of plus and minus magnetization are the basic idea for digital information storage. The two principal methods for reversing the magnetisation are rotation and domain-wall motion and the predominant mechanism depends on the material and its dimensions. Both modes can be examined in terms of energy considerations. The coherent and incoherent rotation of the magnetization only occur in single-domain particles (SDP). A particle is SD below certain dimensions. Above a critical radius a domain wall may exist and the reversal takes place by domain-wall motion. In the coherent rotation mode the atomic spins remain parallel during the reversal process and this may apply only for very small particles. If the particle size increases, incoherent switching mechanisms like curling, buckling and fanning are used. Magnetic thin films with a polycrystalline structure are strongly

exchange coupled (short distance on atomic scale) and consequently their magnetisation reversal will take place by domain-wall motion. This has been studied for a long time for Co–Cr films having a perpendicular anisotropy (e.g. Ref. [30]). In the case of high density recording low noise is a requirement (particulate reversal behaviour is necessary for a sharp transition) and certain magnetic properties (high H_c and M_r). By tailoring the microstructural properties ‘continuous’ thin films can be transferred into a more particulate medium. For high density recording we have to deal with SDP which can be described by the classical nucleation theory (e.g. Ref. [31]). Also the magneto-static interaction (long range) between the particles should be taken into account. The magnetic structures (magnetic domains and written bits) in Co–Cr films are strongly related to the microstructure, morphology and CS. A simple schematic structure (see Fig. 3) of sputtered Co–Cr films consisting of equal-sized columns is used as a model to discuss the possible magnetization reversal phenomena. The upper part of Fig. 3 shows the microstructure with equal column size and shape and a columnar boundary. In this case, the interaction between the columns occurs by exchange and mag-

Fig. 3. Model of the sputtered Co–Cr film in which the morphology is determined by the compositional separation (CS). The upper part shows the ideal microstructure without CS. The lower left-hand side represents only CS at the columnar boundaries while the lower right-hand side shows CS at the columnar boundaries as well as CP-like structures in the columns.

netostatic 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 realised by CS or separation (by voids) of the columns, which has been shown also in the case of Co–Cr–X media for LMR. In the case of CS a non-ferromagnetic Cr-rich composition is present between the columns (Fig. 3, lower left-hand side). The more complicated CP structure of one column in combination with a Cr enriched column boundary is shown in Fig. 3 (lower right-hand side). This type of complicated structures have many consequences for the switching behaviour 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/in²) 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 behaviour.

2.3. Coercivity in thin film media

The coercivity in a magnetic material is a very important parameter for applications but it is very difficult to understand its physical background. It may be varied from nearly zero to more than 2000 kA/m in a variety of materials. First of all, the coercivity is an extrinsic parameter and is strongly influenced by the microstructural properties of the layer such as crystal size and shape, composition and texture. These properties are directly related to the preparation conditions. Material choice and chemical composition (and inhomogeneities) are responsible for the M_s of a material and this is also an influencing parameter of the final H_c . If we only consider crystalline material, then the crystalline anisotropy field (H_k) plays an important role. It is difficult to discriminate between all these parameters and to understand the coercivity origin in the different

thin-film materials in detail. As has been seen in an ideal SDP which switches coherently, $H_c = H_k$, if a field is applied in the easy axis direction. Depending on various factors incoherent switching occurs and the H_c decreases. Even in a matrix of particles, with magnetostatic interaction, the coercivity will be influenced. Multidomain particles and thin films will switch by domain-wall motion and again the coercivity decreases in comparison with the H_k . In addition, for thin films surface and interface properties have an influence on H_c . The above leads to the assumption that H_c can only be determined by means of the macroscopic hysteresis loop in combination with the theory of micromagnetism [32]. Knowledge of the microstructural properties of the material is indispensable. In the first place the size and shape of the magnetic unit (crystal, column) plays an important role. In SDP the H_c increases to a maximum at a critical particle-size diameter. Further increase in the diameter results in a multidomain particle (MDP). When the SDP diameter is decreased, it finally becomes super-paramagnetic. At this stage the reversal takes place by thermal agitation which again leads to a lower H_c . In the case of an MDP the H_c is determined by pinning mechanisms of the domain wall. These mechanisms are determined by the magnetically inhomogeneous regions like columnar boundaries, chemical inhomogeneities, stacking faults etc. The H_c for polycrystalline thin films were recently discussed in [33].

2.4. Aspects of medium noise

In magnetic recording systems three types of noise must be considered: medium, head and electronic noise. Medium noise is the most important factor influencing the performance of the recording system. Medium noise has its origin in several mechanisms and depends strongly on the type of medium used. Local structural and chemical variations in the medium cause distortions in the magnetisation pattern resulting in noise in the signal. At high densities the so-called particulate noise plays an important role and is not only restricted to particle media. It is also important in thin film media because it is likely that the columns behave as uncoupled magnetic SDP. The noise is determined by the properties of the individual particles and the relatively weak magneto-

static interactions between the particles. For a thin film medium the $SNR = n \cdot tw \cdot \delta \cdot \lambda / 2 = n \cdot tw \cdot bl \cdot \delta$ (see part (e) of Ref. [6]). From this it can be seen that the SNR is directly proportional to the packing density n (ratio between magnetic and non-magnetic material). For a pure particulate medium the $S/N \propto n^{1/2}$. In general, smaller particles have a statistical reduction of noise given the same bit area. This rule is valid if the medium does not have exchange coupling and has only weak magnetostatic interaction. However, very small particles give a continuous decrease in coercivity until the particles become superparamagnetic. Higher densities and lower noise consequently result from smaller bits containing crystallites with smaller sizes. For example, a bit cell in the Co-based medium used for the IBM 1.19 Gbit/in² demonstration disk [1] consists of about 1900 grains with a grain size of about 20 nm. Consequently, for a 10 Gbit/in² thin-film medium a grain size of about 10 nm is necessary. (Smaller grain size is not possible due to the superparamagnetic limit.) In this case there will be about 600 grains in a bit area.

2.5. Critical size for isolated Co–Cr column

There are various critical dimensions for a ferromagnetic particle in relation with its magnetic behaviour. The precise size depends on the shape and the material. First of all the critical boundary between SDP and MDP (at a diameter of about 0.1 μm). The domain structure lowers the magnetostatic energy but increases the exchange energy caused by the domain walls. The reversal in such particles mainly takes place by domain-wall motion. At a certain smaller diameter the SDP switching mode changes from coherent into one of the incoherent modes (critical size in the order of 15 nm). Another critical dimension appears between the ferromagnetic and the superparamagnetic state of the particle; in other words the thermal activation energy kT exceeds the particle anisotropy energy barrier. When using the Néel–Arrhenius law for time decay in particle assemblies $1/\tau = 10^{-9} \exp(K_1 V/kT)$ [34] the estimated superparamagnetic limit of Co–Cr is $\approx 440 \text{ nm}^3$ 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 [35]. A typical critical diameter for materials mostly used in recording media (given a certain thickness) is about 5 nm. The reversal of the magnetisation in this type of particle is the result of the thermal motion. Consequently the intrinsic coercivity strongly depends on the particle diameter and can be described by a model given in [36]. For more detail description please refer to [37].

3. Macro–meso–micro magnetic properties

In order to understand the relation between the *macromagnetic properties* (e.g. hysteresis loop properties such as M_s , M_r , H_c measured with Vibrating Sample Magnetometer), *micromagnetic properties* (obtained by simulation and calculation) and *mesoscopic properties obtained by experimental methods* (Lorentz microscopy, Magnetic Force Microscopy (MFM) and Anomalous Hall Measurements (AHM)) it must be realised that they 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 (micromagnetic behaviour). Moreover the thin film media discussed here are composed of small crystallites consisting of a 3D periodic arrangement of (magnetic) atoms (mesoscopic behaviour). In the simplest case, each magnetic atom has the same local environment in which the neighbouring 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 (see Fig. 1) for such media is about $3 \mu\text{m}^2$ the recorded information is obtained from 2500 crystals. The micromagnetic calculations are mostly obtained from 20–100 of such crystals because of the computer capacity and a 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 smaller volumes can be obtained. Only then is it possible to find a more definitive relation between the microstructure, local chemical composition and the magnetic behaviour on a length scale more related to high density recording. Given 10 Gbits/in² (expected in the year 2000) the fundamental structural dimensions (crystal size and surface topology), intrinsic magnetic structures (domains) and the bit dimensions are approaching similar sizes. Research was started in the author's laboratory in three complementary areas: (a) investigation into the relation between shape and magnetic behaviour in artificially etched 'bits' [38], (b) measurement and micromagnetic modelling of the switching behaviour of individual magnetic entities in sub-micron Hall-crosses [39], and (c) observation of microstructure and written bits by AFM and MFM [40,41]. These mesoscopic measurements serve as an input for micromagnetic simulations [42,43]. An overview of these three fields of interest is given in [44].

3.1. Anomalous Hall effect measurements

In order to study the reversal mechanism in more detail the hysteresis loop of sub-micron dimensions of Co–Cr samples was determined with the so-called Anomalous Hall Effect (AHE) [39]. Various Co–Cr samples were measured [45]. For this purpose, a series of small cross-shaped Hall structures (see Fig. 4) was prepared. The smallest structure, prepared by E-beam lithography and ion-beam etching, was $0.2 \times 0.2 \mu\text{m}^2$. A measured AHE hysteresis loop (Fig. 4) of $300 \text{ nm} \times 300 \text{ nm}$ 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 magnetization rotation and domain nucleation in the soft magnetic initial layer. This has been further used for micromagnetic simulations [43]. By recording AHE-loops of these samples, the reversal can be clarified to a

Fig. 4. An AHE hysteresis loop (bottom) of a 300 nm^2 etched Co–Cr structure with an enlargement of a small area of the loop (top) in the field range of 170–190 kA/m. Here also the AHE voltage of one homogeneous Co–Cr column is indicated as well as the noise level.

great extent. For this purpose, we used the step size distribution of the magnetization in the AHE loop [43,45]. To interpret the results, simulations are necessary to check whether intuitive models are correct or need extension [43]. The number of magnetisation changes is much larger (about a factor of 4–6) than the number of columns in the measured sample [43–45]. This indicates that the column is not the smallest magnetic unit in this particular Co–Cr film. A microstructure which could explain this is the CP structure. The small changes can be explained by reversible rotation of regions with in-plane anisotropy [46], which have no perpendicular anisotropy.

From the measured AHE loop we also found negative ΔM 's. This might indicate the presence of magnetic volumes at the limit of superparamagnetism. According to the step size, their volume could be around 20 nm^3 . With a micromagnetic model, the influence of some microstructural parameters on the observed magnetic behaviour is investigated. The results obtained by CS studies and AHE measurements are supporting each other [43,45]. In micromagnetic simulation the CS is incorporated and with this addition the AHE results can be calculated

and are qualitatively in agreement with the measured results [43].

3.2. 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, the texture

Fig. 5. Model structure of 25 Co–Cr columns. Each column consists of small elements (cubes). The column have been modified in Co and Cr-rich areas (black and white) and an initial layer (grey) at the bottom of the column having an in-plane anisotropy. The simulated in-plane and perpendicular loop from such a model are shown in the lower part of the figure.

and the composition are incorporated into the model by varying the exchange, the magnetization and the anisotropy locally. The micromagnetic model [42,43] used consists of particles (Co–Cr columns) in the shape of cubes of $(50\text{ nm})^3$ which are subdivided into cubic elements of $(5\text{ nm})^3$ with uniform magnetization (see upper part of Fig. 5). Exchange between the particles is modelled by assigning an exchange to a few randomly chosen element-pairs which are on the particle boundaries. The initial growth layer, as present in our Co–Cr, is modelled by assigning an in-plane easy axis to cubes of 8 elements in the bottom two rows of elements in the model. These cubes are exchange coupled to the particle they belong to. This partly overcomes the well-known problem of a too high H_c/H_k in micromagnetic simulations [47] since it reduces 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 set-up. Because the AHE measurements prove that the average magnetic unit size is not equal to the column size, each column is modelled as a Co-poor matrix with 3 Co-rich platelets. Although the parameters used are not completely equal to the dimensions and distribution of the CS they show reasonable agreement with the experimental AHE loop (see lower part of Fig. 5).

3.3. Magnetic force microscopy

The principle of the MFM used is described in [48] and 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 [49,50]. The images obtained from the MFM are composed from the gradient of the force which 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 struc-

Fig. 6. MFM observation (a) of a perpendicular Co–Cr medium consisting of 400 nm track width and a linear density of 200 kfrpi ($bl \approx 130\text{ nm}$) From the same surface the bit area is shown ($400 \times 130\text{ nm}^2$) in the AFM image (b).

tures (domain structure). An overview of the performance of the MFM used for various recording media is given in [40]. 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 behaviour in all practical measurements so far and the ‘resolution’ for measuring magnetic details is better than 30 nm [41]. The top photograph in Fig. 6. shows written bits (220 kfrpi) in a track of 400 nm width 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 nm) Ni–Fe underlayer [51]. 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 areal density of 12 Gbit/in². 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 also the surface topology was measured (Fig. 6b). From this we measured an average columnar/crystal diameter (at the surface) of about 45 nm (see the bottom Fig. 6). The bit size of the 200 kfrpi bit (area about 0.05 nm²) 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 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 diameter is necessary. For 100 Gbit/in² the bit area must decrease by more than a factor of 8. Assuming the same track width of 400 nm, the bit length should be 15 nm. A crystal diameter of about 7 nm is necessary.

4. Conclusions

The PMR mode can reach extremely high densities and will be an important competitor for LMR mode specially in the extreme high density application. 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 sub-micron Co–Cr samples on the basis of the measured 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/in² for 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 which should be optimised are the coercivity, the remanence, the film thickness and columnar size and shape. The sharpness and shape of the written transition are determined by the grain morphology, magnetic coupling of the texture of the grains. The particular behaviour will be finally 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 (2500 nm²) is predicted with bit lengths smaller than 50 nm.

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