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2011 J. Phys. D: Appl. Phys. 44 455002

(http://iopscience.iop.org/0022-3727/44/45/455002)

J. Phys. D: Appl. Phys. **44** (2011) 455002 (4pp) doi:10.1088/0022-3727/44/45/455002

Magnetic orientation in advanced recording media

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Received 10 August 2011, in final form 30 September 2011
Published 28 October 2011
Online at stacks.iop.org/JPhysD/44/455002

Abstract

The purpose of this work is to determine the distribution of easy axis orientation in advanced perpendicular recording media capable of supporting a high areal density of 400–500 Gbits inch^{-2}. The distribution of easy axis orientation has been investigated via the measurement of the variation of coercivity H_C with angle to the perpendicular to the film plane. At H_C there is no effect from the strong demagnetizing field. Simulations based on the assumption that each grain reverses coherently are compared with the experimental results. We find that the value of coercivity is reduced approximately 10–13% with a variation of angle to the perpendicular of 10°. The standard deviation of the distribution of the easy axis directions is between 5° and 7°.

1. Introduction

There is enormous growth in the areal density in hard disk drive storage. Advanced perpendicular magnetic recording media (PRM) are made with small grain sizes ($D < 8$ nm) and high thermal stability in order to increase capacity [1, 2]. New characterization techniques are required due to the presence of a large demagnetizing field, $H_D = -4\pi M_S$ [3]. There have been a number of attempts using both theoretical and experimental measurements to correct the demagnetizing effects in PRM [4, 5]. However, the demagnetizing field cannot be determined correctly due to its non-uniformity near the film surface. Therefore, H_D is a critical factor to be considered in the development of new characterization techniques.

One of the most important parameters in PRM is the switching field distribution (SFD) within the medium. The SFD originates from the distribution of grain size, variation in the anisotropy constant K, intergranular magnetostatic and exchange interactions and the effects of crystalline axis dispersion leading to a distribution of the intrinsic switching field $H_K (=\alpha K/M_S)$, where M_S is the saturation magnetization, K is the anisotropy constant and α is the alignment factor or the grain orientation factor. The crucial factor is the distribution of easy axis orientation of the thin film as a small deviation from the perpendicular orientation leads to a large change in the switching field. For example following Stoner–Wohlfarth theory, a deviation of 10° leads to a reduction in H_K of a single grain of 30% [6]. For perpendicular media, the recording medium is based on CoCrPt alloys with co-sputtered SiO_2 in order to control the grain size and separate the grains. The magnetization reversal of each single domain grain can be described by Stoner–Wohlfarth theory due to the small grain size, and the effect of SiO_2 leads to exchange decoupling [6].

There have been a number of attempts to measure of the distribution of magnetic orientation from the measurement of the physical grain orientation from x-ray rocking curves $\Delta\theta_{EA}$ [7]. Attempts have been made to measure the distribution of magnetic orientation from the variation of remanence ratio (M_r/M_S) with angle [8, 9]. This measurement is difficult to interpret due to the small change in M_r/M_S with angle (<5% in 10°) and the fact that the true zero field (H_T) cannot be determined due to the demagnetizing field. Consequently, numerical modelling is required to obtain the distribution. In a previous work we have shown that the variation of coercivity with angle gives a much larger change (15% in 10°) and has the advantage that the global $H_D = 0$ at this point on the loop, although surface values may be non-zero [10]. In this previous report we described the variation of H_C with angle but here we now derive the distribution of easy axis directions. Exchange coupling of the grains will also affect the effective distribution which is that which will affect the recording performance.

We now present a new technique to extract the effective easy axis distribution from the variation of coercivity with angle. We have calculated the angular dependence of coercivity for a range of distributions of easy axis orientation assuming that each grain reverses via coherent rotation. By comparison with the experimental variation of H_C via modelling, we can find the distribution of effective easy axis orientations.

2. Experimental

Four different advanced perpendicular recording media capable of supporting a high areal density of 400–500 Gbits inch^{-2} were studied with different levels of SiO_2 (samples 1, 2, 3 and 4). The storage layer is based on a CoCrPt alloy deposited on 2.5 AlMg alloy disks coated with a Ni–P smoothing layer along with co-sputtered SiO_2. The use of SiO_2 will result in the control of the exchange coupling between grains and the distribution of grain size. Samples 1 and 2 had only a storage layer with small and large grain size, respectively. For samples 3 and 4, a capping layer was sputter deposited on top of the recording layer. Our objective in undertaking this work is to show that our measurement procedure and the analysis/modelling that we have used shows that the distribution of easy axis orientation can be obtained to high resolution thereby distinguishing small sample-to-sample variations. It is not our intention to determine the exact details of the samples giving rise to the distribution.

Magnetic measurements were made at room temperature using an ADE Model 10 vibrating sample magnetometer (VSM) with a maximum applied field of 2.0 T and a noise base of 10^{-6} emu. The hysteresis loop for each sample was measured without correction for the demagnetizing field H_D, due to its zero value at H_C. We used a saturation field H_{sat} of ± 8 kOe and a field step of 100 Oe. The measurement was repeated at different angles (θ) between the applied field and the normal to the film plane. The angle was varied from -10° to $+10^\circ$ with a step size of 2°. For these small angles the change in H_D is negligible and there will be only a small change in the response of the detection coils. The curve fitting routine used went through $\sim$10 points on each loop and reproducibility checks indicated that the measurements of H_C were accurate to ± 2 Oe. We found that the results for all samples are consistent with the Stoner–Wohlfarth theory [6]. The coercivity is largest at 0° and decreases with increasing angle. All samples were measured using exactly the same procedure and field sweep rate to negate the effects of magnetic viscosity in the films.

3. Computer simulations

In order to investigate the effect of the distribution of easy axis orientations of the grains a computational simulation of the variation of coercivity with angle was employed to compare with the experimental results. The numerical method is performed under the assumption that each grain reverses via coherent rotation and calculated according to the Stoner–Wohlfarth model [6].

The calculation is essentially a complex, large-scale integral since, as the sample is rotated, a previously aligned grain moves out of alignment with the applied field and a previously misaligned grain may become aligned. Following standard thermal activation theory for a single grain aligned with the applied field,

$$H_C = \alpha H_K \left[1 - \left(\frac{25kT}{KV} \right)^{1/2} \right] \tag{1}$$

where $H_K = 2K/M_S$ is the anisotropy field, K is the anisotropy constant, M_S is the saturation magnetization, V is the grain volume, α is the alignment factor derived from the Stoner–Wohlfarth model, k is Boltzmann‘s constant and T is the temperature. Equation (1) shows that the value of H_C is strongly dependent on the parameters V and K (and their dispersion). However, the term inside the brackets is independent of the orientation of the field; any angular dependence will arise from the angular dependence of the pre-factor. For the aligned case the pre-factor is equal to H_K, and for any arbitrary angle it can be determined using Stoner–Wohlfarth theory. Strictly, equation (1) applies only for a measurement time of 100 s that gives rise to a factor 25. However, this factor originates from the Neel–Arrhenius law where it appears in an exponential. Hence for a measurement time of 1000 s only an 8% deviation results inside the square root. This is much less than the accuracy in the value of K that is used as a fitting parameter.

For each sample all parameters are constant with angle other than the term α, which depends on the field orientation. Normalizing to $H_C(0)$ allows different samples to be compared. $H_C(0)$ is an easy parameter to establish in the experiments as it is the maximum value of $H_C(\theta)$. Neither exchange nor dipolar coupling is included in the calculations.

The normalized coercivity at any angle is given by

$$h = -\frac{(1 - t^2 + t^4)^{1/2}}{(1 + t^2)} \tag{2}$$

where $h = H_C(\theta)/H_C(0)$ and $t = \tan(\theta)^{1/3}$ and θ is the angle between the easy axis and the applied field. The coercivity must be calculated as the field for which $M = 0$. Following [11] it can be shown that, for systems with a negligible population of superparamagnetic particles, this leads to the condition

$$H_C = \tilde{H}_C^{i} \tag{3}$$

where $\tilde{H}_C^{i}$ is the intrinsic coercivity given by equation (1) and the tilde denotes the median value.

The distribution of easy axis orientation, $f(\varphi)$ is taken as a Gaussian distribution with standard deviation (σ) varying from 0° to 10°. Because the median is equal to the mean for a symmetric distribution such as the Gaussian and because the temperature-dependent factor in equation (1) is independent of the orientation we can write the coercivity as

$$H_C = H_C(0)\langle h(\theta)\rangle \tag{4}$$

where $\langle h(\theta)\rangle$ denotes the mean value. We note that for non-symmetric distributions the relationship between the median and the mean will result in a constant factor which can be absorbed into $H_C(0)$.

The actual effective distribution, $f(\varphi)$, has to be obtained by fitting the data to one of these families of curves. The situation is made more complex by the effect of intergranular exchange coupling and dipolar coupling. The exchange coupling will tend to keep the grains aligned parallel hence narrowing the distribution, as compared with the distribution of crystallographic orientation. Dipolar interactions will generally be demagnetizing and will tend to broaden the distribution.

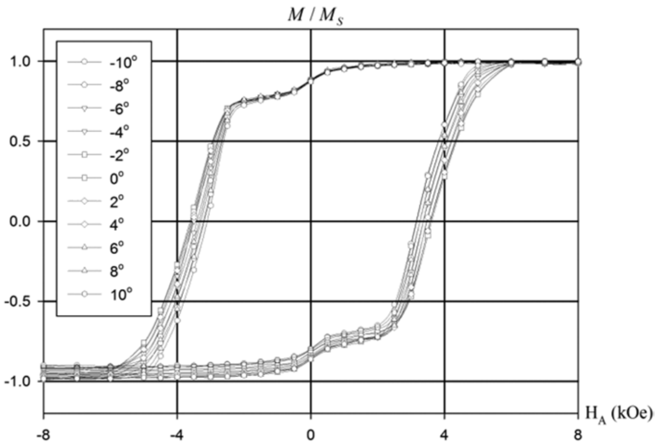

Figure 1. Hysteresis loops at different angles at 25 °C for sample 3.

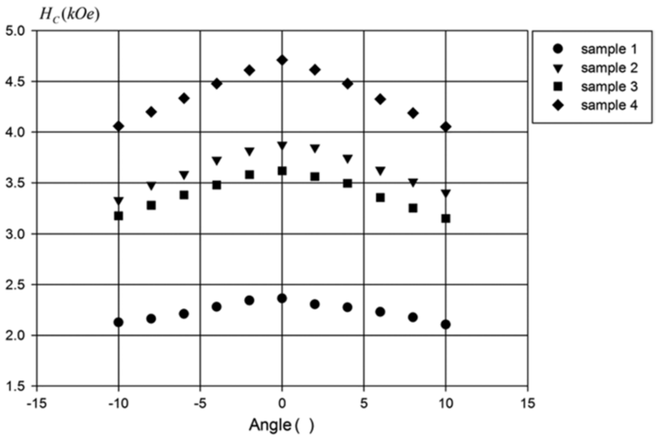

Figure 2. Variation of coercivity with angle for all samples.

4. Results and discussion

Figure 1 shows a typical hysteresis loops for sample 3. The coercivity has a maximum value at 0° and reduces with increasing angle up to 10°. The loop has a reversal at low field. The low field reversal evident in figure 1 arises from a soft magnetic capping layer on those films. This layer is fully saturated at fields below 2 kOe and hence will not affect the variation of H_C for the hard layer which occurs at fields around 3.5 kOe. The large H_D shears the loop to a slope of $\sim 4\pi$. At the coercivity H_C, global H_D is zero. Reproducibility tests showed that the coercivity was accurate to ± 2 Oe, i.e. 0.15%. All measurements were made at a constant sweep - rate of 250 Oe min^{-1}.

The variation of coercivity with angle between $-10°$ to $10°$ for all samples is shown in figure 2. It is interesting to note that the reduction in coercivity of all the samples changes between 10% and 15% for a misalignment of 10°. These results agree well with the previous work of Carter *et al* [10]. The variation of coercivity with angle is much larger than that of the remanence over the same angular range leading to a much smaller error than is the case for remanence measurements.

In order to investigate the effect of the distribution of c-axis orientation, the computer simulations are compared with the experimental results.

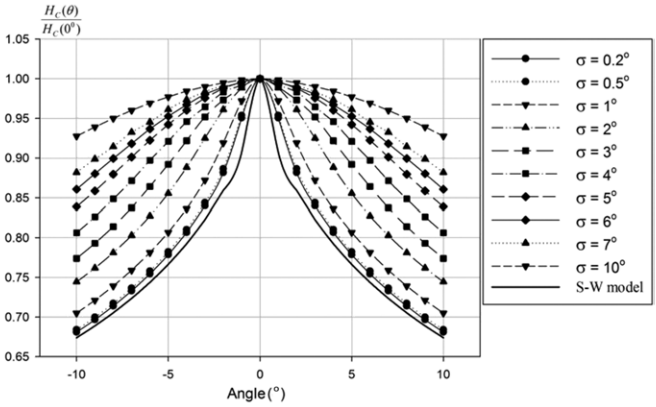

Figure 3. Calculation of the variation of coercivity with angle θ ranging from $-10°$ to $+10°$.

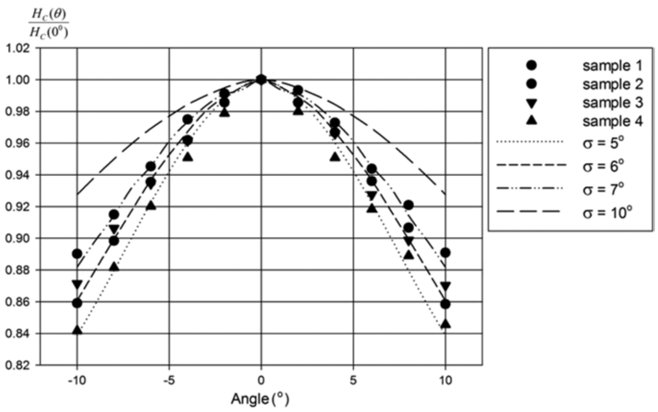

Figure 4. Variation of H_C with θ from experimental and calculated results.

Figure 3 shows the calculated variation of the normalized coercivity with angle from $-10°$ to $+10°$. As seen in figure 3, the variation of $H_C(\theta)$ follows the Stoner–Wohlfarth model for $\sigma = 0$ which is the aligned case and produces a highly peaked curve as expected, also showing the expected 30% reduction in H_C at an angle of 10°. The variation is seen to broaden as the distribution of easy axis orientation increases. These results indicate that when the c-axis orientation is narrow ($\sigma = 0.2°$), the magnetization reversal closely follows Stoner–Wohlfarth behaviour [6].

We find excellent agreement for all samples which are consistent with σ lying between 5° and 7° as shown in figure 4. The experimental results of the variation of H_C with angle for samples 1 and 4 agree with the calculated values with standard deviations of the distribution of easy axes orientation of 7° and 5°, respectively. Samples 2 and 3 display similar behaviour with $\sigma = 6°$. This shows that advanced perpendicular recording media have a low dispersion in the orientation of the easy axis direction. Of course the value of σ represents the dispersion of only 63% of the orientation of the grains. The full width of the dispersion is better represented by 3σ which includes 99% of the grains; this gives a dispersion of $\sim 18°$ either side of the perpendicular to the film plane. This is a relatively large value.

Also our value is the effective dispersion which includes the effects of exchange and dipolar coupling between the

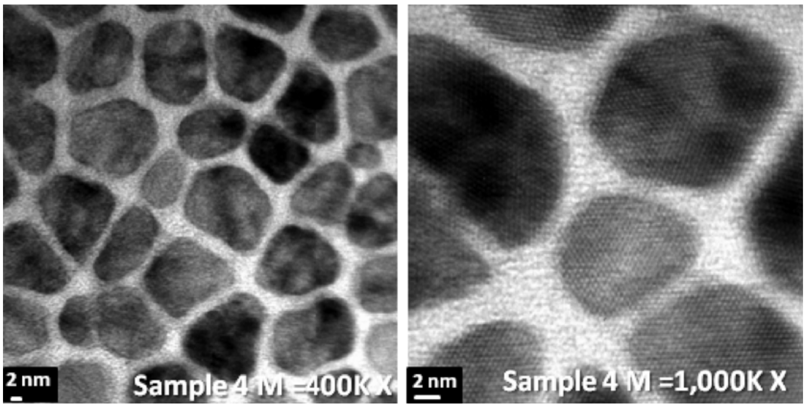

Figure 5. HRTEM in-plane image of sample 4 showing the silica segregation.

grains. Exchange coupling will tend to keep the grains aligned parallel whereas dipolar effects will tend to broaden the effective distribution by tending to lower the coercivity. Exchange coupling will also tend to lower H_C due to the weak link effect or co-operative reversal. However, this only occurs for the case of strong coupling which will not apply to these films due to the silica segregation of the grains. However, it is the effective distribution that will control the recording performance. A typical transmission electron microscopy image for the samples, in this case sample 4, is shown in figure 5. The images shown in figure 5 are typical of current state-of-the-art co-sputtered, high-density perpendicular recording media. In this case the median diameter of the grains D_m was 4.5 nm and the standard deviation of the lognormal distribution $\sigma = 0.27$. The images also show that the SiO_2 segregates the grains almost completely with an average grain-to-grain separation of ~2 nm so that these systems are almost fully exchange decoupled. All samples examined had a similar microstructure. A low exchange coupling means that the distribution of easy axis orientation measured by our technique will closely reflect the orientation of the *c*-axis of the grains.

A further interesting consequence of this measurement procedure and analysis is that it may provide a route for the measurement of coupling effects. The physical distribution of crystallographic axes, if determined to sufficient accuracy by x-ray diffraction rocking curves, can be subtracted from our measurement with the difference being due to coupling effects. These measurements are in progress.

5. Conclusion

We have shown that measurements of coercivity as a function of angle provides a sensitive measure of the distribution of magnetic easy axes in perpendicular recording media. This method has the advantage of not requiring the measurements to be corrected for the effect of the global demagnetizing field, H_D. A relatively simple numerical analysis, when compared with the experimental data, allows the effective distribution of magnetic easy axes to be obtained.

Acknowledgment

The authors wish to acknowledge the supply of recording media by WD Media Research of San Jose, CA.

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