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Magnetic Characterization of Perpendicular Recording Media

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***Abstract*—In this paper, we describe techniques for the magnetic characterization of perpendicular recording media. Such measurements made using traditional techniques, such as the vibrating sample magnetometry (VSM) and alternating gradient force magnetometer (AGFM), have to be corrected for the sample shape demagnetizing factor, which is often found not to be equal to -4π. For measurements other than the simple hysteresis loop, such as remanence curves, this correction must be carried out in real time and we describe the method by which this can be achieved and the process for achieving the correct demagnetization of perpendicular films prior to measurements of the isothermal remanent magnetization curve. A further complication is that real perpendicular media have a soft underlayer beneath the recording layer, which swamps and confuses signals from instruments such as VSM or AGFM. Hence, we describe the construction and use of a magnetooptical Kerr effect magnetometer, which does not penetrate significantly into the soft layer and enables the perpendicular layer to be measured independently. We describe the properties of a traditional alloy perpendicular medium and a Co–Pd multilayer system, which in the latter case exhibits multiple switching behavior. We also address the issue of the effect of the soft underlayer on the coupling in similar longitudinal films and find that the presence of the underlayer induces significant additional coupling effects that may well give rise to an increase in noise in recorded signals.**

***Index Terms*—Coupling effects, magnetic characterization, perpendicular recording media, switching field distribution.**

I. Introduction

THE MAGNETIC characterization of perpendicular recording media is of significant scientific and technological interest as technologies for high density recording above 100 Gb/in^2 are sought [1]. These measurements are complicated due to the strong demagnetizing fields which result in a significant change in the value of the total field. In principle it is possible to correct a magnetization curve by assuming that the demagnetizing field H_D is $-4\pi M$. However, while this may facilitate the measurement of the hysteresis loop and gives a value for the coercivity where the demagnetizing field is zero, it is more complex to determine other key parameters such as isothermal remanent magnetization (IRM) and DC demagnetization (DCD) curves, the switching field distribution (SFD) and ΔM curves, which determine coupling effects [2]. To measure these quantities, it is necessary to correct the field in real time as the field is swept and to have an appropriate procedure for the demagnetization of the media prior to the measurement of the IRM curve. In certain types of film, and particularly multilayer films, the correction $-4\pi M$ appears not to be applicable. Of course the magnetostatic self energy does indicate that the demagnetizing field is equal to $-4\pi M$. However, the presence of strong intergranular exchange coupling results in cooperative reversal and a distorted hysteresis loop if the demagnetizing field H_D is taken as $H_D = -4\pi M$. The origin of this variation in the demagnetizing field arises from the exchange coupling within the media.

When a film is prepared suitable for information storage, a relatively thick soft underlayer is grown beneath the perpendicular film. In this instance, any signal from a conventional magnetometer from the perpendicular layer will be swamped by that of the soft layer and conventional magnetometry cannot be used. We have found that magnetometers based on magnetooptical Kerr effect (MOKE) can successfully be used for the characterization of the perpendicular layer since the penetration of the laser light, typically a few hundred Angstroms, does not extend all the way through the soft magnetic layer. However, measurements of this type, while in principle allowing the characterization of the perpendicular layer in the presence of a soft layer, do not accurately reflect the switching behavior of the medium in use. For any significant applied field ($H_A > 1$ kOe), the soft layer becomes partially magnetized and it is essential to measure remanence curves in order to accurately characterize the effect of the soft layer on the switching in the perpendicular layer and measurements of hysteresis loops can be misleading.

The presence of soft layers beneath a hard layer can also have significant effects on the intergranular coupling. In such structures, it is possible that intergranular exchange coupling can occur for compositionally segregated grains via the soft underlayer. It is also possible that simple dipolar coupling can occur via the underlayer. In either case, the result is that long range spatial correlation occurs between the grains leading to the generation of medium noise [3].

II. Experiment

The samples examined in this work were: single-layer CoCrPt (20 nm) and CoCrPtTa (50 nm) alloy films grown on Ti (7 nm) buffers and a set of multilayer films of [Co(0.3 nm)/Pd(1.0 nm)] $\times$ 20 grown on an ITO buffer and on a soft underlayer (240 nm). It is expected that the alloy film containing Ta will exhibit greater intergranular exchange decoupling compared with the sample without Ta. This arises because it is believed that the Ta

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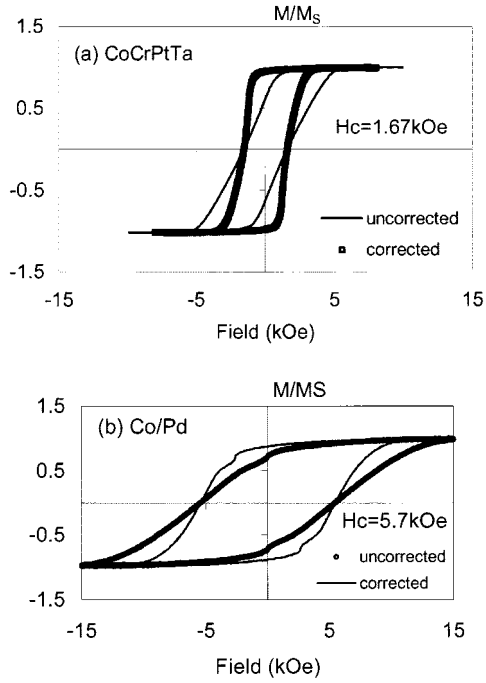

Fig. 1. Hysteresis loops of (a) CoCrPtTa alloy film (b) Co–Pd multilayer film taken from AGFM.

occupies lattice sites or interstitial sites where the Cr may sit, leading to an increase in Cr segregation to grain boundaries [4].

An alternating gradient force magnetometer (AGFM) and a MOKE magnetometer were used for the characterization of the samples. The AGFM is a commercial product of Princeton Measurements Systems Corp., model M2900. The software of the AGFM has been modified to take measurements so that the internal field of the perpendicularly magnetized samples can be obtained and zero internal field can be determined by taking account of the assumed demagnetizing field (H_D) of a perpendicular thin film, which is $H_D = -4\pi M$. The correction is carried out in real time during hysteresis loop and remanence curve measurements by calculating the total field $H_T = H_A - H_D$ at each field step. Fig. 1 shows hysteresis loops from the AGFM for the CoCrPtTa alloy and the Co–Pd multilayer films without the presence of soft underlayers. In both these cases, the use of $H_D = -4\pi M$ appears to give a "reasonable" result. However, for the CoCrPt alloy, which is believed to have stronger intergranular coupling than the CoCrPtTa sample, a distorted loop results if a correction $H_D = -4\pi M$ is used and a reasonable loop can only be obtained if $H_D = -0.1{*}4\pi M$ is applied. This is a reflection of the effects of strong intergranular exchange coupling. Hence, to make our measurements we have had to use a value of H_D based on what appears to be "reasonable" from the shape of the loop. The values used are almost certainly not correct but do allow features of the switching to be determined from remanence curves.

A MOKE magnetometer has been developed for the magnetic characterization of perpendicular media. A 15-mW HeNe laser of wavelength 633 nm was used as the light source and a Thorlabs laser intensity stabilizer model CR200-A used to reduce the drift in intensity to less than 0.2%. The polarization of the incident beam is chosen as s-polarized to eliminate the transverse Kerr effect. A nearly crossed analyzer is used in the reflected beam path and the rotation of the polarization is sensed by a photo-diode detector. An electromagnet with a rotation facility was used in order to take measurements at different angles of incidence. The rotation stage has a wide angle ($\pm 60°$) of beam access. Software with a demagnetizing field correction similar to that used on the AGFM has been developed to allow hysteresis loops and remanence measurements of perpendicular media to be obtained. The MOKE magnetometer does not give a direct measurement of the magnetic moment so that the system must be calibrated for each sample measured, by measuring the saturation moment using a conventional magnetometer. It cannot be stressed too highly that the determination of M_S must be very accurate. Any inaccuracy will alter the shape of the hysteresis loops determined by MOKE but will dramatically effect the measurement of remanence curves as both values of the applied field and zero field will be in error. Once the saturation magnetization of the sample is known, the MOKE loop height can be converted into a measurement of the relative magnetization. This also allows for the calculation of the demagnetizing factor for the correction of MOKE data, and this factor can then be used in remanence curve measurements. The demagnetizing field correction for the MOKE technique demands high stability of the laser intensity and the stabilizer is essential for most measurements. A schematic diagram of the MOKE system is shown in Fig. 2. As an interesting aside we have observed that the hysteresis loops for the decoupled CoCrPtTa alloy film obtained from the AGFM and the MOKE show a substantial discrepancy in terms of the value of H_C obtained (AGFM $= 1.67$ kOe, MOKE $= 2.11$ kOe). We have conducted an extensive investigation of the origin of this effect and can find no cause in our instrumentation or procedures. Also, we obtain good agreement for all other samples studied. At this time, we cannot account for this effect.

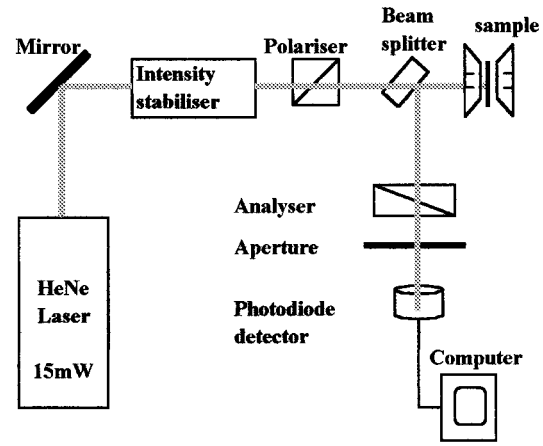

Fig. 2. Schematic diagram of the MOKE system used for the characterization of perpendicular media.

Before undertaking IRM curve measurements, the samples were demagnetized using the DC cyclic erasure process (DCE) [5]. This is done by taking M–H loops at gradually reduced values of maximum field. The reduction of the maximum field was undertaken in steps of 100 Oe.

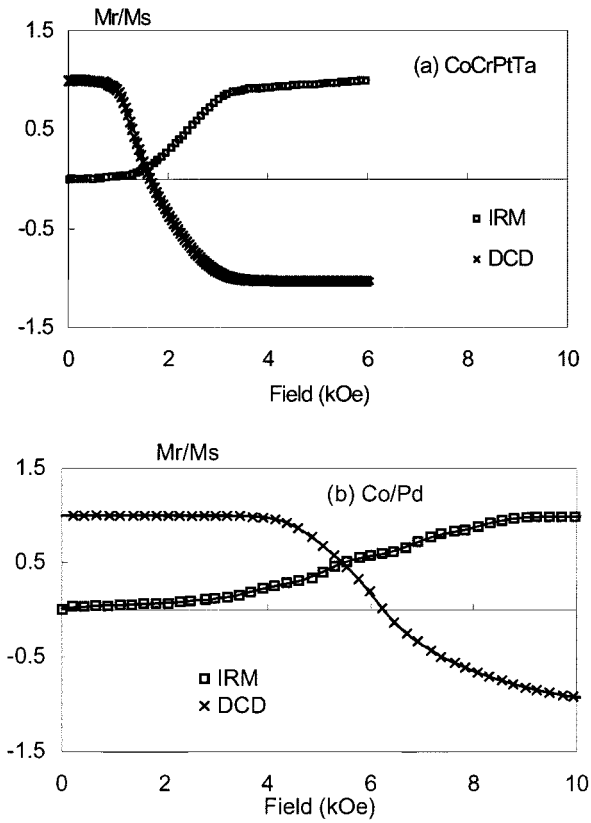

Fig. 3. Remanence curves obtained from the AGFM for (a) CoCrPtTa alloy film (b) Co–Pd multilayer.

III. Results and Discussions

A. Switching Field Distribution From the AGFM

Remanence curves obtained from the AGFM for the same samples as those for which hysteresis loops are shown in Fig. 1, appear at Fig. 3. The resulting SFDs obtained by differentiation are shown in Fig. 4. The data show interesting effects in that for the alloy film, the SFD from the DCD curve is observed to be narrower than that from the demagnetized case and moves to lower fields. However, there appears to be a shoulder in the curve at about 2.4 kOe and continued switching to high fields resulting in an apparent bimodal distribution. This effect is probably due to a combination of coupling and demagnetizing effects. The former is known to narrow the distribution and move it to lower fields. Demagnetizing effects arise as the material approaches saturation and flux closure ceases, leading to the need for fields greater than the normal switching field to allow for the increase in magnetostatic energy. This can lead to an apparent bimodality. For the multilayer film, multimodal switching is observed from the demagnetized state. However, once saturated the DCD data shows that the coupling smooths the switching with demagnetizing effects again resulting in nonsaturation of the remanence up to 10 kOe.

The multimodel switching from the demagnetized state for the multilayer films presumably due to variations in the interlayer coupling through the stack. This interpretation remains to be confirmed. However, once saturated the switching becomes uniform but a long tail in the SFD at high fields is still present due to a similar increase in magnetostatic energy as saturation is approached to that which occurs in the alloy film.

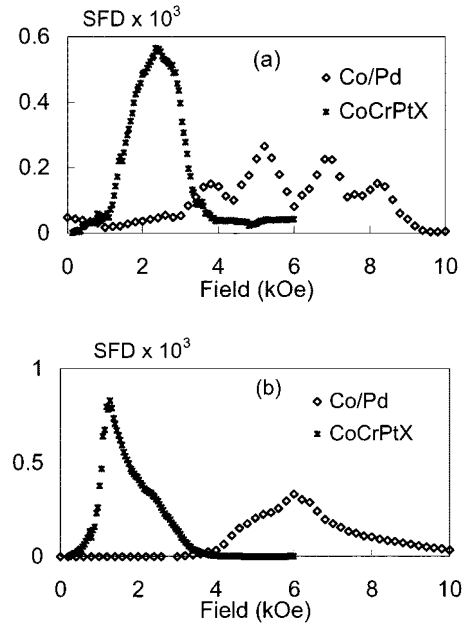

Fig. 4. Switching field distributions from the AGFM remanence curves for the alloy and multilayer films (a) SFD from IRM (b) SFD from DCD.

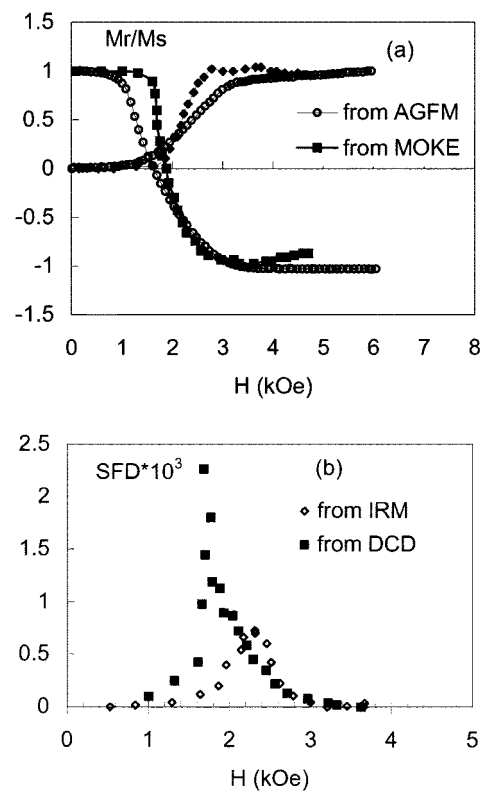

Fig. 5. (a) Remanence curves for CoCrPtTa alloy sample from the AGFM and MOKE. (b) SFD from the remanence curves of MOKE.

B. Switching Field Distribution From MOKE

Fig. 5(a) shows IRM and DCD curves for the CoCrPtTa alloy sample without a soft underlayer obtained from the AGFM and

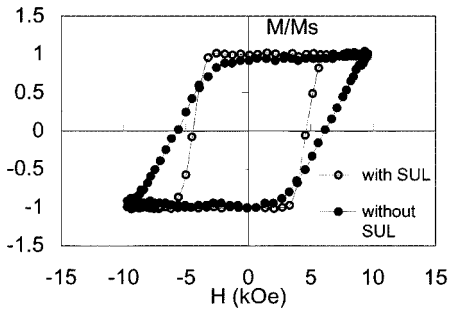

Fig. 6. Hysteresis loops from the MOKE for the Co–Pd multilayer sample with and without soft underlayer.

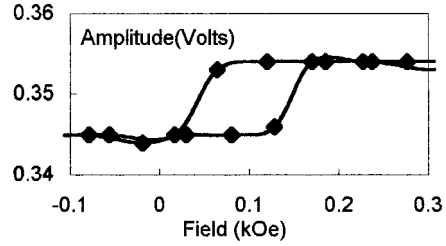

Fig. 7. MOKE loop for the soft underlayer of a multilayer sample taken around zero field at 75° angle of incidence.

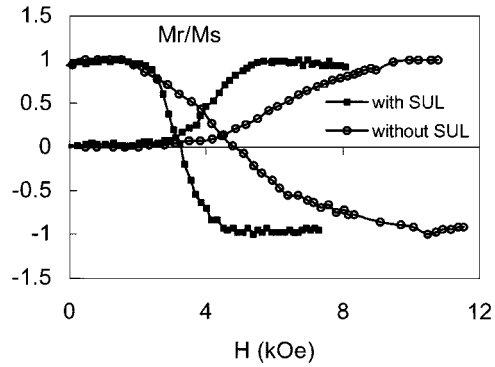

Fig. 8. Remanence curves of the Co–Pd multilayer sample with and without a soft underlayer taken with the MOKE magnetometer at normal incidence.

the MOKE systems. All data have been obtained assuming a demagnetizing field $H_D = -4\pi M$. For both remanence curves, we find that the MOKE shows apparent switching at different fields than the AGFM. Also, the SFDs obtained from the MOKE [Fig. 5(b)] are narrower. This effect is somewhat puzzling; however, these variations are consistent with the differences in the measured loops described in Section II. Measurements are ongoing to establish the origin of this effect, which may lie in part in an error in determination M_S and, hence, H_D.

C. Effect of a Soft Underlayer

For this part of the study, we have used the CoPd multilayer system. Samples of an identical structure were prepared with and without a soft underlayer. It is not possible to measure films with a soft underlayer using an AGFM or a VSM as the moment of the soft underlayer completely dominates that from the recording layer. Hence, in this part of the work, we have used only our MOKE system. Also, because we do not know the saturation moment of the recording layer for the system with the soft underlayer, we are unable to correct any of our data for the effects of the demagnetizing field.

Fig. 6 shows the MOKE hysteresis loops for the multilayer with and without the underlayer. From these data, it appears that the soft underlayer gives rise to a reduction in H_C and a significant narrowing of the SFD. Assuming that the presence of the underlayer does not give rise to any significant change in the structure of the multilayer, the most probable cause of these effects is strong exchange coupling in the multilayer stack via the underlayer.

From these data, it is also clear that the MOKE system is able to measure the recording layer without "seeing" a contribution from the soft underlayer. However there is a concern that the laser should penetrate right through the recording layer so that surface effects do not dominate. We have examined this possibility by measuring loops with an angle of incidence of 75° to the normal to the film plane. In this configuration, we find that we can see effects in the loop from the soft underlayer and we are able to separate the loop of that part of the underlayer immediately beneath the recording layer. This minor loop for the system is shown in Fig. 7. We note that the coercivity as measured via the half width of the loop is about 50 Oe.

For the case of a 75° angle of incidence, we also observe significant jumps in remanence curves after the application of fields greater than 500 Oe and up to those fields required to bring the sample to about 0.6 of the maximum remanence. We believe these effects are due to the moment of the soft underlayer being pulled out of the plane of the film when the field is applied and then relaxing back into either easy direction when the applied field is zero. Very much smaller jumps are observed at normal incidence, indicating that this is an effect from the underlayer.

Fig. 8 shows both IRM and DCD curves (uncorrected) for the samples with and without the soft underlayer measured using the MOKE. Fig. 9 shows the SFDs obtained from the data in Fig. 8. From these figures, it is clear that the underlayer does lead to a significant lowering of the switching fields and a narrowing of the distribution. These effects in combination are almost certainly due to a significant increase in exchange coupling as similar effects have been observed and predicted for longitudinal media [2], [3]. The exact mechanism by which the exchange increases is not clear. It is possible that the morphology of the grains in the multilayer is altered by the presence of soft underlayers leading to a change in intergranular coupling. Alternatively, some form of intergranular coupling via the soft layer may occur. In either case, the presence of the soft underlayer will invariably lead to an increase in dipolar effects which may augment other effects. Unfortunately, due to the fact that we cannot correct for H_D, it is not meaningful to produce ΔM curves in this case.

D. Effect of a Soft Underlayer on Coupling in Longitudinal Films

The effects of a soft underlayer on coupling effects cannot as yet be determined via ΔM for films with perpendicular anisotropy and a soft underlayer. However, we have previously studied traditional longitudinal media with a soft underlayer,

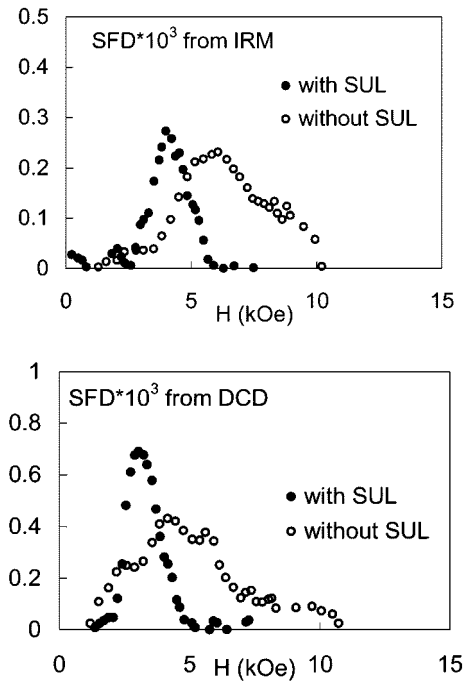

Fig. 9. SFDs obtained from the remanence curves shown in Fig. 8.

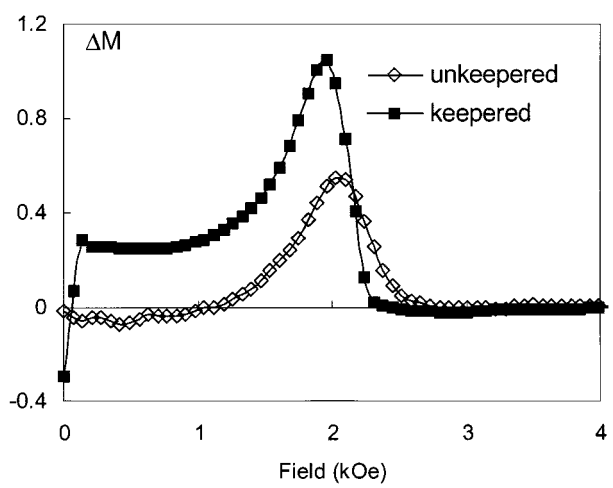

Fig. 10. ΔM curves taken from the longitudinal CoCrPt films with and without a soft underlayer.

i.e., so-called "keepered media" [5]. These films had a CoCrPt recording layer with a NiFe underlayer.

Fig. 10 shows the ΔM curves [6] for films with and without a soft underlayer. From these data, it is clear that the soft underlayer significantly increases the intergranular coupling as shown by the significant increase in the slope of the ΔM curves in the switching region. Two possible mechanisms can account for this effect: there is either some form of exchange coupling via the underlayer, or a dipolar effect. Either would be expected to give rise to a long-range correlation of the magnetization, which would not only affect the measurement of ΔM, but also give rise to increased noise in the films. Similar effects would be expected to occur in films with perpendicular anisotropy.

IV. Conclusion

In this paper, we have reviewed the magnetic characterization of perpendicular recording media using an AGFM and a MOKE magnetometer. We have shown that it is in principle possible to correct data from either system for the effect of demagnetizing field if the demagnetizing factor is known accurately. There remains an urgent need to develop techniques to the determination of H_D. We have also shown that coupling effects play a significant role in the reversal of both alloy and multilayer films.

We have shown that a magnetometer based on MOKE can overcome the difficulties that arise due to the presence of a soft underlayer. However we have observed as yet unexplained differences between coercivities measured using a MOKE magnetometer compared with the data obtained from an AGFM. The origin of these effects is the subject of an ongoing study.

As yet we have been unable to develop techniques for the characterization of coupling effects in perpendicular films with a soft underlayer via either AGFM or MOKE studies. The presence of the soft underlayer prevents the determination of the value of M_S for the perpendicular layer and since the MOKE magnetometer does not measure magnetization (M) directly, a correction for H_D cannot be obtained. However, data for a longitudinal film with a soft underlayer shows that a significant increase in coupling can result.

We have also measured time dependence effects in these samples and maintained the total field at a constant value by correcting the demagnetizing field in real time as the data is taken. In so doing we have observed that for both alloy and multilayer films, the variation of M with lnt is nonlinear. When the correction is not undertaken, the variation is closer to linear in lnt. However, even with the use of our correction software the total field cannot be kept constant to better than ± 5 Oe, and this resolution is insufficient for the accurate determination of the activation volume.

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