Determination of Activation Volumes of Reversal in Perpendicular Media

J. D. Dutson, K. O'Grady, Bin Lu, Yukiko Kubota, and C. L. Platt

***Abstract*—We discuss a method for the determination of activation volumes of reversal in perpendicular media. This method does not require correction for the self-demagnetizing field normally associated with these media. This is achieved by performing time dependence measurements at a constant level of magnetization. From the difference in time taken for the magnetization to decay to a fixed value at two fields separated by a small increment ΔH, the activation volume can be determined. We report data for both CoCrPt alloy films and a multilayer film, typical of those materials under consideration for use as perpendicular media. We find activation volumes that are consistent with the hysteresis curves of the materials. The activation volume scales qualitatively with the exchange coupling. The alloy films have significantly lower activation volumes, implying that they would be capable of supporting a higher data density.**

***Index Terms*—Activation volume, fluctuation field, magnetic characterization, perpendicular recording media.**

I. Introduction

RECENTLY, significant effort has been focused on the development of perpendicular media as a method of increasing the areal densities in magnetic recording above 100 Gb/in^2 [1]. The magnetic characterization of these materials is complicated due to the presence of a large demagnetizing field. In principle, the magnitude of the demagnetizing field, $H_D = -4\pi M$. However, when this correction is applied it leads to overcorrected, sheared loops [2]. There have been a number of attempts to measure remanence curves and time dependence effects in perpendicular media: In work by Wu *et al.* [3], $H_D = -4\pi M$ is assumed and time dependence measurements reported where the applied field was continuously corrected to maintain the total field, H_T, constant. However, it was found that the total field could not be kept constant to sufficient accuracy to give smooth data. Le Phan *et al.* [4] corrected the applied field to linearize time dependence data in $\ln(t)$. For systems with a narrow range of energy barriers such as films with perpendicular anisotropy, this is not the case [5], [6]. Van der Veerdonk *et al.* [2] used a factor N ($H_D = -4\pi NM$) to adjust the value of the demagnetizing field where $0 \leq N \leq 1$. This simple correction cannot be true over the entire range of the magnetization of the sample. The size of the demagnetizing field must change throughout the switching region and from its definition the global value must be $-4\pi M_s$ when the sample is saturated.

In the study reported here, we use a different philosophy to characterize the media, in that we determine time-dependent behavior as a function of magnetization. This has the significant advantage that the demagnetizing field is in principle constant for a given value of M although local variations may still occur due to differing domain structures giving rise to the same value of M. Parameters such as the fluctuation field, H_f, can be determined independent of the demagnetizing field and related back to the hysteresis loop.

The experimental method used in this work is based on the waiting time method for the determination of H_f, which is a fictitious field that represents the coupling of thermal fluctuations to the magnetic moment. It is from this field that the activation volume $V_{\rm act}$ can be determined:

$$H_f = \frac{kT}{M_{\rm sb} V_{\rm act}} \tag{1}$$

where k is Boltzman's constant, T is the temperature, and $M_{\rm sb}$ is the saturation magnetization of the bulk material. The activation volume corresponds to the minimum volume that can reverse coherently and, hence, is a measure of the minimum bit size that can be written to a medium.

The waiting time method was developed by el Hilo *et al.* [7] for the determination of H_f in systems where the variation of M is not linear in $\ln(t)$. In this method, H_f is found from the difference in time taken for the magnetization to fall to a fixed value at applied fields separated by an increment ΔH

$$H_f = \left. \frac{\Delta H}{\ln\left(\frac{t_1}{t_2}\right)} \right|_M \tag{2}$$

where t_1 and t_2 are the times taken for the magnetization to decay to the chosen level. These quantities are shown in Fig. 1.

This method is similar to the equation of state technique of Folks *et al.* [8] but has the advantage of using absolute values of differences in time rather than a small difference in the gradient of the M versus t curve. The method of Folks *et al.* has previously been used by others to characterize films used for magnetooptic recording [6], [9].

II. Experiment

We have studied three samples that are typical of those media that are most likely to be implemented in recording systems. Two CoCrPt alloy films and a Co/Pd multilayer film

Manuscript received January 10, 2003. The travel of J. Dutson was supported in part by the U.K. IOP Magnetism Group E.P. Wohlfarth memorial fund.

J. Dutson and K. O'Grady are with the Physics Department, University of York, Heslington, York YO10 5DD, U.K. (e-mail: jdd103@york.ac.uk; kog1@york.ac.uk)

B. Lu, Y. Kubota, and C. Platt are with Seagate Research, Pittsburgh, PA 15217 USA

Digital Object Identifier 10.1109/TMAG.2003.816292

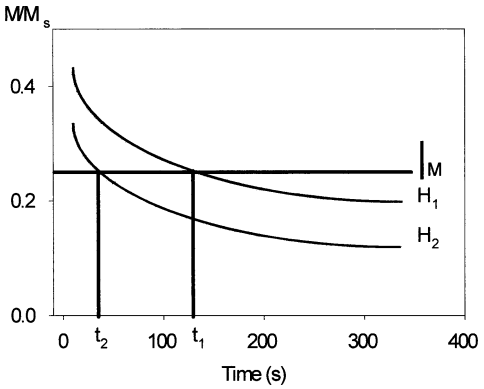

Fig. 1. Schematic representation of the determination of H_f using the waiting time method.

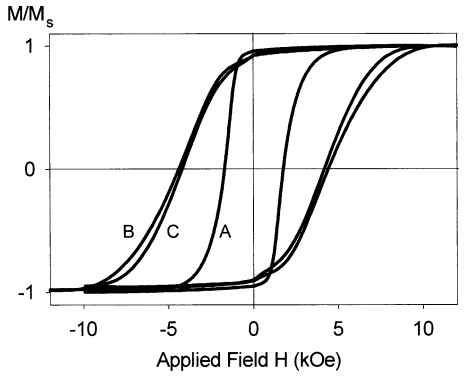

Fig. 2. Hysteresis curves for sample A, B, and C.

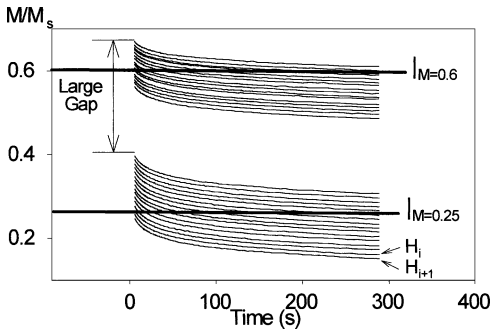

Fig. 3. Typical time dependence data for sample B.

were selected for study. Sample A was a single layer, CoCrPt alloy whose structure is Substrate/Underlayers/CoCrPt(20 nm) and has a relatively low coercivity of $H_c = 1.63$ kOe. From the slope of the hysteresis curve at the coercivity, $((dM/M_s)/dH) = 1.06 \times 10^{-3}$ Oe^{-1}, we infer that this sample has grains with significant intergranular exchange coupling. It is expected that this sample would exhibit a significantly larger activation volume due to this coupling effect [10]. Sample B was also a single layer CoCrPt alloy film but with significantly different magnetic properties. It has a structure of Substrate/Underlayers/CoCrPt(20 nm) and has a significantly higher coercivity $H_c = 4.35$ kOe. From the slope of the loop for this sample $((dM/M_s)/dH) = 3.26 \times 10^{-4}$ Oe^{-1}, it appears that it has significantly less exchange coupling and consequently we would expect this sample to have a lower activation volume. Sample C is a Co/Pd multilayer film with structure: glass/seedlayer/ML stack (19 nm) and had similar magnetic properties to the high coercivity alloy with a coercivity of $H_c = 4.2$ kOe and $((dM/M_s)/dH) = 3.67 \times 10^{-3}$ Oe^{-1}. It is expected that this sample would have similar activation volume to the alloy film from the hysteresis curve alone [10]. The hysteresis curves for the three samples are shown in Fig. 2.

The measurements were performed on a customized, Princeton Measurements Corp., M2900 alternating gradient force magnetometer. The time dependence measurements were made by first saturating the sample, applying the required field, H_1, and measuring the decay of magnetization for 300 s. This process was then repeated at a new field $H_2 = H_1 + \Delta H$ over the entire range of the switching field distribution. To obtain correct values for the fluctuation field the selection of the field steps is critical. It is a requirement of the waiting time method that the field steps (ΔH) be $< 5\%$ of the width of the switching field distribution [9]. To obtain a sufficient number of intercepts between the line of constant M and the data, the field steps must be significantly smaller. To enable the entire switching range to be covered, the field steps were grouped together with a number of closely spaced measurements separated by large field steps. Therefore, for Sample A, the field range was from 0 kOe to -5 kOe with field steps (ΔH) of 20 Oe between data points and 500 Oe steps between each group of data points. For sample B the fields were from 0 to 9.5 kOe and with ΔH of 30 Oe and 1 kOe between the groups, and for sample C the required field steps were for 0 to -6.5 kOe with $\Delta H = 20$ Oe between measurements and 700 Oe between groups. An example of typical experimental data for sample B is shown in Fig. 3.

For each value of magnetization, the fluctuation field was obtained from a graph of H versus $\ln(t)$ to obtain an average over several values for $\Delta H/\ln(t_1/t_2)$. To obtain reliable data, only those levels of magnetization with a minimum of four intercepts were used.

Waiting time measurements should be made at constant M irreversible and not constant M. Where this is not the case, a correction should be applied as described by Antel *et al.* [11]. For the samples examined here, it was found that the change in M was entirely irreversible and, hence, the correction was not required.

III. Results and Discussion

Fig. 4 shows the variation of activation volume with field for samples A, B and C. As can be seen the data is clustered together in sections, which correspond to the groupings of the field steps selected. It is noticeable for all films that the activation volume for values of M close to $+1$ are significantly greater than those in the middle of the switching region, i.e., $M = 0$. This first stage of reversal must involve the nucleation of reverse domains and the data indicates that the value of $V_{\rm act}$ for this process is significantly larger than that near H_c. This would imply that domains nucleated at this point would be large compared with the difference in domain sizes for small field steps around H_c.

The sample with the greatest slope of the loop at the coercivity, sample A, had the largest activation volume of reversal

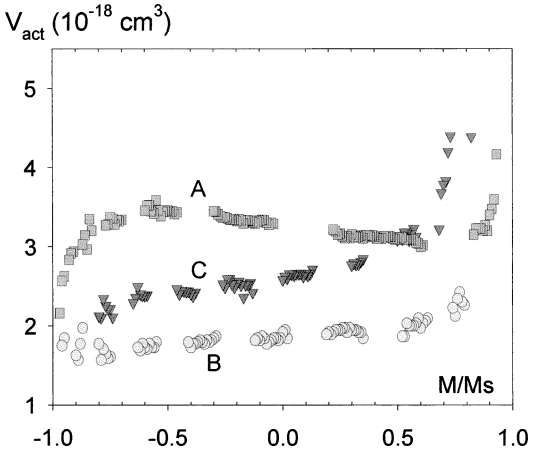

Fig. 4. Activation volumes of reversal for samples A, B, and C.

near $M = 0$. The comparison between the decoupled alloy and multilayer film with similar loops, samples B and C, shows that the multilayer sample has a significantly higher activation volume, about 50% larger than the alloy film. This can be explained by the fact that the perpendicular anisotropy in multilayer films is obtained from exchange coupling between layers and this coupling leads to an increase in the size of the smallest entity that can reverse. For the weakly coupled alloy film (Sample B) the smallest activation volume is observed, implying that the domain sizes in this film will be the smallest. This has a significant effect on which types of film would be most suitable for a commercial hard disk. Of course, it is not possible to quantify the coupling in the systems via the usual ΔM technique because the remanent points cannot be determined without knowing the demagnetizing field. However, from our data, it would appear that a simple comparison of the hysteretic properties of potential media and even of loop shape is insufficient to allow for the selection of potential media.

The value of $V_{\rm act}$ near to negative saturation ($M < -0.8$) is seen to fall, particularly for sample A. The origin of these small values of $V_{\rm act}$ lies in the fundamental micromagnetic behavior of the films. As negative saturation is approached, domains in the original positive direction are reduced in size until eventually reversal must occur by rotation. A significant reduction in the self energy of the film will occur even when very small residual domains are present. Hence, magnetostatic effects will favor the formation of such domains. This rotation of small residual domains gives rise to a reduced activation volume as observed in Fig. 4.

We wish to emphasize that our discussion of the data has not required a consideration of the demagnetizing field due to our measuring at constant M. The activation volumes can be mapped onto the measured hysteresis loop using M alone, avoiding the use of inaccurate values of H_D.

REFERENCES

[1] R. W. Wood, J. Miles, and T. Olson, "Recording technologies for terabit per square inch systems," *IEEE Trans. Magn.*, vol. 38, pp. 1711–1718, July 2002.

[2] R. J. M. van de Veerdonk, X. Wu, and D. Weller, "Switching field distributions and ΔM measurements for perpendicular media," *IEEE Trans. Magn.*, vol. 38, pp. 2450–2452, Sept. 2002.

[3] J. Wu, L. Holloway, H. Laidler, K. O'Grady, S. Khizroev, J. K. Howard, R. W. Gustafson, and D. Litvinov, "Magnetic characterization of perpendicular recording media," *IEEE Trans. Magn.*, vol. 38, pp. 1682–1686, July 2002.

[4] K. Le Phan and C. Lodder, "Iterative method for intrinsic viscosity measurements on perpendicular recording media," *IEEE Trans. Magn.*, vol. 38, pp. 2003–2005, Sept. 2002.

[5] M. El-Hilo, K. O'Grady, and R. W. Chantrell, "The origin of nonlinear $\ln(t)$ behavior in the time dependence of magnetization," *J. Magn. Magn. Mater.*, vol. 109, pp. 164–168, 1992.

[6] R. Sbia, M. Mochida, Y. Itoh, and T. Suzuki, "Relaxation time and thermal stability in magneto-optical recording media," *IEEE Trans. Magn.*, vol. 36, pp. 2279–2281, Sept. 2000.

[7] M. El-Hilo, K. O'Grady, and R. W. Chantrell, "Fluctuation fields and reversal mechanisms in granular magnetic systems," *J. Magn. Magn. Mater.*, vol. 248(3), pp. 360–373, 2002.

[8] L. Folks and R. Street, "Analysis and interpretation of time dependent magnetic phenomena," *J. Appl. Phys.*, vol. 76, no. 10, pp. 6391–6395, 1994.

[9] T. Thompson, K. O'Grady, S. Brown, P. W. Haycock, and E. W. Williams, "Optical and magnetic measurements of time dependence in magneto-optical thin films," *IEEE Trans. Magn.*, vol. 28, pp. 2515–2517, Sept. 1992.

[10] M. El-Hilo, K. O'Grady, and R. W. Chantrell, "Demagnetised states and activation volumes in thin film media," *J. Magn. Magn. Mater.*, vol. 120, pp. 244–246, 1993.

[11] W. J. Antel, H. Laidler, K. O'Grady, C. Verdes, and R. W. Chantrell, "Determination of activation volumes in thin film media," *J. Appl. Phys.*, vol. 91, no. 10, pp. 7080–7082, 2002.