

Thermal Relaxation in the Strong-Demagnetizing Limit

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Abstract— We have developed a new technique that simulates the thermal magnetization decay (magnetic viscosity) within bit transitions that have a strong demagnetizing field H_d approximately equal to the remanent coercivity of the recording medium. This technique uses a vibrating-sample magnetometer to measure the viscosity while allowing the applied field to decay logarithmically at a rate consistent with the measured magnetization decay. The decaying applied field simulates the decaying H_d of a broadening bit transition. The magnetic decay measured using this technique remains logarithmic in time, but is almost a factor of 4 smaller than that measured using a constant applied field. These results imply that the standard viscosity measurement is inappropriate when estimating the amount of thermal broadening due to H_d within a transition. We have also developed a model of the magnetization decay in a large decaying H_d using a modified Arrhenius-Néel rate equation with a single energy barrier that has explicit dependence on the magnetization. The model predicts logarithmic magnetization decay consistent with that observed experimentally and also indicates that the viscosity measured using this technique may be a measure of the average energy barrier preventing thermal switching.

Index Terms— Magnetic viscosity, demagnetizing field, bit transition.

I. INTRODUCTION

Manufacturers of disk drives are steadily increasing the areal recording density of media. An 8 Mbit/mm² (5 Gbit/in²) drive has been demonstrated under laboratory conditions [1] and up to 160 Mbit/mm² (100 Gbit/in²) is now being discussed as a reasonable goal [2]. One result of higher bit densities is that the volume of a bit must be proportionately smaller for a given medium thickness. Because a smaller magnetic volume is more susceptible to thermal reversal, thermal stability of the bit will decrease for higher densities and thermal erasure may become significant [3].

Another consequence of higher bit densities is the requirement for sharper bit transitions. A sharper transition will lead to a larger demagnetizing field H_d at the transition, which may accelerate thermal reversal. In the limit of an initial infinitely sharp bit transition, the transition will relax to a point of minimum stability such that the maximum demagnetizing field H_d^{max} is approximately equal to the remanent coercivity H_{cr} of the medium [4]. We shall call this situation the strong demagnetizing limit for a bit transition. The magnetization in the transition will continue to broaden with time because of thermal activation assisted by the demagnetizing field. In response, the demagnetizing field will decrease since the gradient of the magnetization decreases.

Several experimental techniques can be used to measure how thermal decay affects recorded data. One technique consists of using a spin stand and measuring the time decay of the voltage signal from an actual written bit. However, spin stand

measurements can be problematic and have the potential for ambiguous or misleading results, particularly when attempting to characterize the fundamental limits to recording density. For example, transitions might display little observable decay with time, not because of good media thermal stability, but rather because the head field gradients produced broad transitions for which the strong demagnetizing limit does not apply. In addition, the presence of the head itself may contribute to non-thermal signal decay. Passage of previously recorded transitions under a high permeability head will cycle the magnetization within the transition [5]. Such cycling may result in AC erasure of the transition and possible loss of signal.

Another technique to characterize thermal decay consists of using a vibrating sample magnetometer (VSM) to measure the magnetization (M) decay under application of a constant field H . H simulates the effect of the demagnetizing field within a bit transition. Logarithmic decay with time is usually observed and the magnetization can be reasonably fit to the function $M(H, t) = M_0(H, t_0) - S_M \log(t/t_0)$, which gives $S_m \equiv S_M/M_r$, the magnetic viscosity normalized to M_r , the remanent magnetization.

We measured S_m vs. H and show the results in Fig. 1. The media that was used for all our viscosity measurements consisted of DC magnetron sputtered CoCr₁₀Ta₄ (25 nm thick) with a Cr underlayer (50 nm thick). We deposited the media onto oxidized Si wafers at 250 °C. The magnetic parameters were as follows: $H_{cr} = 107$ kA/m (1350 Oe), $M_r \delta = 8.6$ mA (0.86 memu/cm²) (δ is the magnetic layer thickness), Squareness $\equiv M_r/M_{sat} = 0.75$. The maximum in S_m occurs near H_{cr} and for this particular film is approximately 6%. We have observed maximum values of S_m ranging from 4 to 7% depending on the film deposition conditions.

Although the results of a conventional VSM viscosity measurement can be used to characterize the vulnerability of

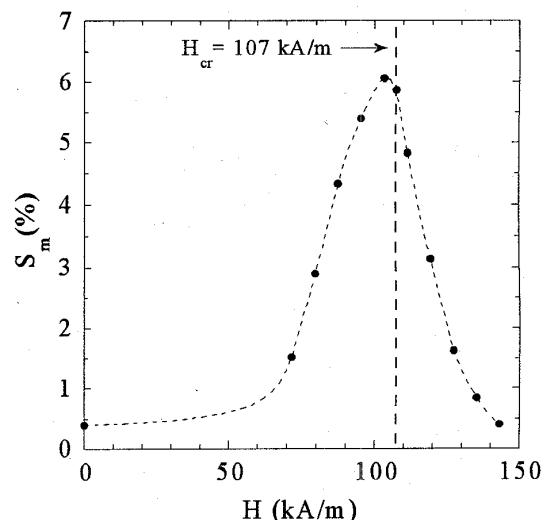


Fig. 1. Magnetic viscosity (S_m) vs. constant applied field (H) for the CoCr₁₀Ta₄ described in the text.

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uniformly magnetized media to thermal reversal, that measurement does not accurately characterize the thermal decay for an actual bit transition where the decay rate is not constant with time. The gradient of the magnetization at the transition is the source of the demagnetizing field; when the transition broadens, the demagnetizing field decays. Our more accurate approach, which uses the VSM to characterize the thermal decay for a bit transition, consists of letting H decay with time at a rate that is consistent with the measured magnetization decay.

II. EXPERIMENTAL PROCEDURE AND RESULTS

To determine what field decay rate is consistent with the magnetization decay rate in the strong-demagnetizing limit, consider the one-dimensional track-averaged representation of a bit transition shown in Fig. 2. We assume that at time $t = 0$, the transition is sharp enough to be "demagnetization limited": the maximum demagnetizing field is $H_d^{max} = H_{cr}$ with initial transition parameter a_0 (see Fig. 2 (i)). Using the Williams-Comstock approximation [4], [6] and taking into account thermal broadening of the transition for $t > 0$ by letting the transition parameter increase with time, we have $H_d^{max}(t) \approx M_r \delta / (2\pi a(t)) \approx M(a_0, t) \delta / (2\pi a_0)$ (see Fig. 2 (ii)). This result follows from the assumption that the transition is roughly linear over much of its length. Therefore, we have $H_d^{max}(t) \propto M(a_0, t)$, so that the maximum demagnetizing field within a transition is proportional to the magnetization at some fixed point. Recalling that $M(a_0, 0) = M_r$ and $H_d^{max}(0) = H_{cr}$, we have the more suggestive rate equation:

$$\left(\frac{1}{H_{cr}} \right) \left[\frac{\partial H_d^{max}(t)}{\partial \log(t)} \right] = \left(\frac{1}{M_r} \right) \left[\frac{\partial M(a_0, t)}{\partial \log(t)} \right] \quad (1)$$

For our VSM-based simulation of thermal erasure within a bit transition, we let the applied field $H(t)$ assume the role of $H_d^{max}(t)$. A correct simulation will then have the field decay at a rate equal to the magnetization decay rate.

The protocol used to determine the proper field decay rate was as follows. After we saturated the magnetization in one direction, we applied $H \approx H_{cr}$ in the opposite direction and let the field decay according to $H(t) = H_{cr} - S_h \log(t/t_0)$, where t_0 is the amount of time H was applied before it was allowed to decay and $S_h \equiv S_h/H_{cr}$ is the chosen field viscosity normalized to H_{cr} . (H_{cr} is actually a function of the time scale over which it is measured [7]; we used the H_{cr} that was measured when the dwell time of the field for each point of the remanent loop was about the same as $t_0 \approx 10$ s.) Field changes were made in discrete steps, with an update interval of 5 s for the first 500 s, and 50 s for the next 5000 s. (Faster update times did not significantly affect the results presented here.) The magnetization decay was measured while the field was decaying. The magnetic viscosity S_m was determined as before, since it was empirically determined that the magnetization still decays logarithmically with time. S_h was then adjusted from its initial value and the measurement repeated until $S_h = S_m$. The final viscosity obtained in this way approximates the viscosity within a bit transition in the strong demagnetizing limit.

Measurements using this protocol were made on the same $\text{CoCr}_{10}\text{Ta}_4$ sample that was used for the conventional (constant H) viscosity measurements. The magnetization decay vs. time for different values of field viscosity S_h are shown in Fig. 3. When $S_h = 0\%$, the measurement corresponds to the conventional viscosity measurement that has no field decay. For non-zero values of S_h ,

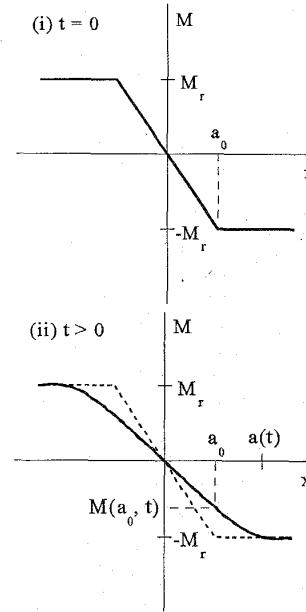


Fig. 2. Magnetization M vs. position x for a demagnetization-limited bit transition at time (i) $t = 0$ (ii) $t > 0$.

the magnetization is also approximately logarithmic in time but displays a range of behavior, from much reduced but finite decay ($S_h = 1.5\%$) to almost no decay ($S_h = 2.5\%$), to even an increase in magnetization with time ($S_h = 7.5\%$). The growth in magnetization with time is due to the finite reversible susceptibility χ_{rev} . This increase is an artifact of the simulation and simply demonstrates that this value of S_h is too large to properly simulate decay driven by demagnetizing fields.

The measured values of S_m for each value of S_h are shown in Fig. 4. The dotted line corresponds to the desired solution where $S_m = S_h$. For our $\text{CoCr}_{10}\text{Ta}_4$, a solution exists for $S_m \approx 1.5\%$. This magnetic viscosity is almost a factor of 4 less than the maximum

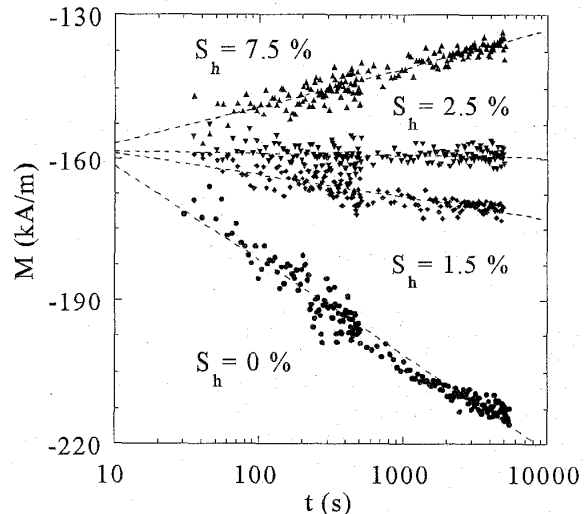


Fig. 3. Magnetization (M) vs. time (t) for various values of field viscosity (S_h). The dotted lines are logarithmic fits of the data.

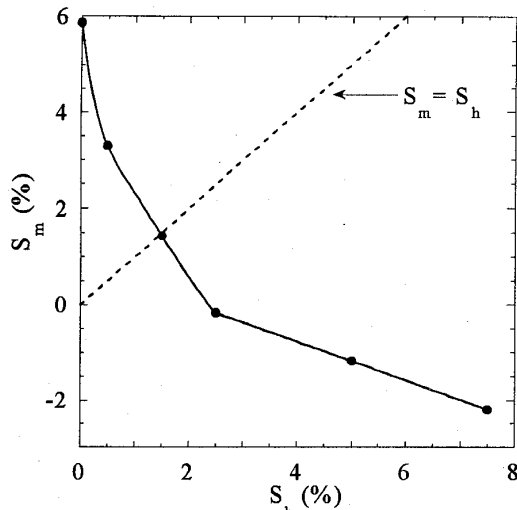


Fig. 4. Magnetic viscosity (S_m) vs. field viscosity (S_h). The dotted line designates the desired solution where $S_m = S_h$.

viscosity measured with a constant H . These results imply that the conventional viscosity measurement may overestimate the amount of thermal decay that can take place within a demagnetization-limited transition.

The relatively small final value for S_m determined using this technique is not the net result of the conventional rate of magnetization decay combined with a small rate of increase in the magnetization due to χ_{rev} . For $S_h = 1.5\%$, the field has decayed approximately 4 kA/m (50 Oe) from H_{cr} by the end of the measurement. Figure 1 shows the conventional values of S_m to be approximately constant over this field range. The effect of χ_{rev} can be determined from Fig. 4. For large S_h and $\chi_{rev} = 0$, the magnetic viscosity should approach the $H = 0$ value of $S_m \approx 0.4\%$ (see Fig. 1). That S_m changes sign and decreases linearly for $S_h \geq 2.5\%$ is due to the finite χ_{rev} . The slope of this line, defined as $\Delta S_m / \Delta S_h$, is approximately 0.4. Assuming that the linearity also applies for $S_h \leq 2.5\%$, the rate of magnetization increase due to χ_{rev} for $S_h = 1.5\%$ is $\Delta S_{rev} \approx (0.4)(1.5\%) = 0.6\%$. Therefore, a linear combination of the conventional rate of decay S_m with the rate of increase ΔS_{rev} would yield a net viscosity of $S_{net} = 6\% - \Delta S_{rev} = 5.4\%$, which is still much larger than the actual measured value of $S_m \approx 1.5\%$. We conclude that the logarithmically decreasing field has fundamentally changed the dynamics of the magnetization switching process.

III. THEORY

Our theoretical approach is similar to that developed previously to explain thermal relaxation in perpendicular media [8], [9]. We model the irreversible magnetization within a demagnetization-limited bit transition using a modified Arrhenius-Néel equation for a single energy barrier:

$$\frac{d\langle M(t) \rangle}{dt} = -\frac{1}{\tau_0} \exp[-U(t)/kT] \langle M(t) \rangle, \quad (2)$$

where $\langle M(t) \rangle$ is the average magnetization of an ensemble of identical "magnetic switching volumes," τ_0 is the fundamental attempt time of the system, and $U(t)$ is the energy barrier to

magnetization reversal for a single switching volume V . Including the effects of the demagnetization field on $U(t)$ gives

$$\frac{U(t)}{kT} = \frac{\mu_0 M_0 V H_{cr}}{kT} \left(1 - \frac{H_d(t)}{H_{cr}} \right) = \alpha \left(1 - \frac{\langle M(t) \rangle}{M_r} \right). \quad (3)$$

Here M_0 is the magnetization of a single switching volume V , α is the ratio of the zero-field energy barrier to kT , and we have used the approximation appropriate for the demagnetizing field within a bit transition $H_d(t)/H_{cr} = \langle M(t) \rangle / M_r$. Equation (2) was solved by using the solution $M(t) = M_r (t_N / t)^\beta$ and the approximation $(t_N / t)^\beta \approx 1 - \beta [\ln(t / t_N)]$ when $\beta [\ln(t / t_N)] \ll 1$. By inserting the logarithmic form of $M(t)$ into $U(t)$ and the power law form elsewhere, it can be shown that a solution exists for $\beta = 1/\alpha$ and $t_N = \tau_0 / \alpha$ (since $\beta = 1/\alpha \sim 1/100$ [3] and $\tau_0 \sim 10^{-9}$ s [7], the solution is valid over the usual time scales of the experiment). Hence, the magnetization will decrease logarithmically in time with a viscosity $S_m \approx \ln(10)/\alpha$ when the energy barrier increases logarithmically in time. This result can be contrasted with the case of a constant $H_d = H_{cr}$, so that $U(t) \equiv 0$ and the magnetization decays exponentially: $M(t) \propto \exp[-t/\tau_0]$. The decay of H_d has dramatically slowed down the decay of the magnetization, in qualitative agreement with the results of the experimental simulation.

A more quantitative comparison between the theory and the experimental simulation must consider the effect of the distribution of α that exist in our measured samples and the effect of χ_{rev} . To this end, we have also analytically solved Eq. (2) with the logarithmic field decay rate fixed to some number different from $1/\alpha$. The average magnetization decay was then calculated for a gaussian distribution of α in a decaying field with $S_h = 1.5\%$. The distribution width normalized to the average α ($\langle \alpha \rangle$) was comparable to the width of dM_r / dH normalized to H_{cr} . We account for χ_{rev} by adding a small logarithmic increase ($\Delta M_{rev}(t) \approx \chi_{rev} S_h \ln(t / t_N)$) to the average magnetization decay of the distribution. The total decay was still found to be logarithmic in time from $t = 10$ s to 10^4 s, in agreement with the experiment. In addition, when $S_m = S_h$ the viscosity was still found to be roughly equal to $\ln(10)/\langle \alpha \rangle$, after the effect of χ_{rev} is removed. A viscosity of $S_m + \Delta S_{rev} = 1.5 + 0.6 = 2.1\%$ implies $\langle \alpha \rangle \sim 100$, a reasonable value for thermally stable media [3].

We recognize that rough approximations were employed in this experimental and theoretical analysis. However, our focus has been to formulate a first order correction to the usual VSM viscosity measurement. Our results emphasize the self-limiting nature of the thermal decay within demagnetization-limited bit transitions.

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