DETECTION OF INDIVIDUAL PARTICLE SWITCHING DURING HYSTERESIS AND TIME DECAY IN Co-Cr THIN-FILMS

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DETECTION OF INDIVIDUAL PARTICLE SWITCHING DURING HYSTERESIS AND TIME DECAY IN Co-Cr THIN-FILMS

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Abstract. – Discrete magnetization jumps of $\sim 10^{-12}$ emu corresponding to the magnetization reversal of individual particles have been resolved in the hysteresis cycle of perpendicularly-oriented, columnar Co-Cr thin films. An experimental sensitivity of 4×10^{-14} emu has been achieved in microscopic Hall samples, containing only a few hundred magnetic columns, by using the anomalous Hall effect voltage generated by a current within the film itself to measure the magnetization. These data are the first experimental demonstration that the reversal of discrete magnetic units in a particulate media can be detected. The technique has been applied to determine the particle switching volumes and the temperature dependence of thermally activated magnetization time decay.

We are pursuing an experimental program whose purpose is a complete microscopic description of the properties of a strongly interacting magnetic many body system. One goal of this program has been the observation of the dc magnetization with sufficient resolution so as to ascertain if there did exist discrete jumps, or steps, corresponding to magnetization reversal or switching of individual magnetic units, i.e., the minimum Barkhausen type jumps of the system. In this paper we report the first direct evidence that for a Co-Cr thin film such discrete magnetization reversals do exist, as evidenced in the observation of jumps in both the hysteresis cycle and in magnetization time decay (MTD). From an analysis of these data we can determine a complete statistical description of the discreet magnetization reversal for any desired temperature and field cycling conditions.

Observed as a slow continuous change in magnetization (at fixed field), (MTD) is thought to arise in particulate media from a statistical distribution of reversals of individual particles, each characterized by an exponential thermal activation law. As first noted by Néel [1] the barrier energy for isolated particles is proportional to the particle volume with the important consequence that only particles in a narrow size range around a characteristic "blocking" volume, will reverse in any time scale of measurement. Néel found that the characteristic switching time was $\approx 10^{-1}$ s for $v = 10^{-18}$ cm^3, but for twice that volume exceeded 10^9 s.

Our goal was to measure the magnetic switching volume and particle switching statistics, by detecting the thermally activated reversal of individual particles, each with a moment of less than 10^{-12} emu. Wouri and Judy [2] proposed that the necessary sensitivity could be obtained by using the anomalous Hall effect as a probe of the sample magnetization in a perpendicularly-magnetized, particulate magnetic thin film. When a current is passed through such a film, the anomalous Hall effect (AHE) generates a transverse voltage, V, proportional to the perpendicular magnetization and the width, w. The abrupt reversal of a single particle of cross-section, $r \times r$, will produce a jump in the AHE voltage:

$$\Delta V = 4\,\pi j R_{\mathrm{AHE}}\ 2SM_{\mathrm{S}}r^2 \,/\, w$$

for current density j, saturation magnetization M_{S} and anomalous Hall coefficient R_{AHE}. The factor, S, is a correction for the effects of the sample geometry [3]. Experimental sensitivity is determined by the size of the AHE cross: no voltage jumps were observed by Wouri and Judy in 5 μ wide Hall samples. Using Co-Cr Hall samples as small as 0.7 μ, we have observed steps in the magnetization indicating the reversal of individual particles.

Co-Cr is a columnar, perpendicular recording medium [4]. Co-Cr films, 1 μ thick, have been deposited onto glass substrates from a $Co_{0.8}Cr_{0.2}$ target by dc magnetron sputtering, with columns up to $r \sim 1\,000$ Å observed in SEM imaging of fractured film edges. The coercivity, $H_c = 570$ Oe and $M_{\mathrm{S}} =$ 410 G. Excess Co-Cr is removed by ion-milling to create cross-shaped AHE samples. The AHE voltage is detected and analysed for jumps in the voltage. For $w = 0.7\ \mu$, a AHE voltage change at 5×RMS Johnson noise limit set by the sample $\left(\sim 0.4\ \mathrm{nV} / \mathrm{Hz}^{1/2}\right)$ corresponds to the reversal of column of $r \sim 100$ Å and $v \sim 10^{-16}$ cm^3 with a moment of about 4×10^{-14} emu or $4 \times 10^6\ \mu_{\mathrm{B}}$.

A hysteresis loop measured using the AHE voltage to determine the Co-Cr magnetization is shown in the inset of figure 1. Expanded scales in figures 1a and 1b identify two regions. In "A" the film is near saturation and magnetization changes are reversable. The hysteresis loop is smooth and shows only the electronic noise of the experiment. In "B" discrete magnetization jumps are observable, with the largest around 1.6 % of the saturation to saturation voltage change, equivalent to a switching volume($r \sim 1\,100$ Å, $v \sim 1.3 \times 10^{-14}$ cm^3 for a 1 μ thick film) comparable to the largest columns. The distribution of jump sizes follows a log-normal distribution typical of the column volume distribution in

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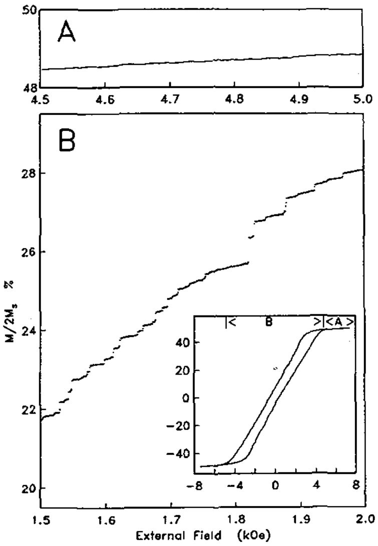

Fig. 1. – Hysteresis loop data measured by the anomalous Hall voltage. Inset: full hysteresis loop. The sample is a 0.7 μ wide cross in a 1 μ thick Co-Cr perpendicularly oriented film. Labels **A** and **B** identify two characteristic regions, displayed with an expanded scale in figures 1a and 1b. For the **A** region, which is near saturation, the magnetization changes are reversable corresponding to tilting of the columns. For the **B** region, where hysteresis is observed, we clearly see the voltage jumps which indicate switching of the magnetic orientation of individual particles.

columnar films. About 85 % of the total magnetization reversal is observed to occur by discrete jumps.

We have previously reported [5] studies of MTD as a function of applied field, temperature, and time scale of measurement (3×10^{-3} s to 3×10^{4} s) in bulk (i.e., area ~ 0.1 cm^2) Co-Cr films. After saturating the Co-Cr film, the field is abruptly reduced to any desired value and the magnetization measured as a function of time.

MTD data obtained for the same Co-Cr material, but from 0 0.7 μ AHE sample, are compared with data for the bulk sample at 300 K and 77 K in figure 2. In a bulk film, MTD is smooth and continuous (Fig. 2, solid lines). While the average decay rates are the same, the continuous magnetization decay observed in bulk Co-Cr films is replaced by a statistical distribution of discrete magnetization jumps due to the reversal of individual particles.

By studying the distribution of jump sizes during MTD as a function of temperature we expect to measure the energy barriers and characteristic switching volumes [1]. To our surprise, we find that in general

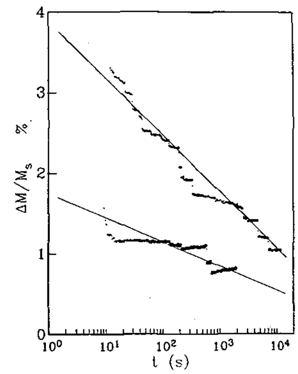

Fig. 2. – Change in magnetization *vs.* log-time showing magnetization time decay (MTD). Curves are for 300 K (upper) and 77 K (lower). The continuous curves are data taken on a bulk (i.e. large area) AHE cross sample while data on a 0.7 μ Co-Cr AHE cross sample is discontinuous clearly showing particle reversals as discrete random jumps in time.

all magnetization jump sizes are present, with a distribution similar to that found for a hysteresis cycle.

As the temperature is lowered, magnetization decay slows. In the Néel model, the larger transitions should be frozen out, as at lower temperatures the "blocking" volume becomes smaller. Again the result is surprising, the total number of transitions decreases from an average of 5 transitions/decade at 300 K to 2.3 transitions/decade at 77 K, but the distribution of jump sizes is not measurably changed.

Clearly, the energy barriers for real, interacting, particles are very different from those for isolated particles. Further studies of the statistics of thermally activated particle reversal as a function of temperature and time range are under way.

Acknowledgments

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