Thermal activation and switching in c-axis Aligned barium ferrite thin film media

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***Abstract*–The thermal activation volume and the magnetic switching volume were measured in c-axis uniaxially in-plane oriented barium hexaferrite thin film magnetic recording media. Excellent agreement among the experimental data obtained independently from the magnetic viscosity measurements and the measurements of the time dependence of coercivity implies that the thermally driven process is the cause of both phenomena. The presence of incoherent switching during magnetization reversal is indicated by the in-plane angular dependence of coercivity and is believed to cause the much smaller activation volume and switching volume than the grain size as determined from a TEM micrograph.**

I. INTRODUCTION

The irreversible switching of magnetization in a ferromagnetic material takes place by thermally-assisted activation across an energy barrier [1]. Some effects of these thermally induced phenomena include magnetic viscosity and time dependence of coercivity.

Barium ferrite thin films have recently attracted attention as future high density recording media due to their chemical and mechanical stability, large coercivity and low medium noise [2]. In this work, the thermal activation volumes (V_{act}) and the switching volumes (V_{sw}) were measured in c-axes uniaxially in-plane oriented barium ferrite thin films with varied grain interaction strength. It was found that V_{act} and V_{sw} are substantially smaller than the grain size of the films, leading to the conclusion that some form of incoherent rotation is responsible for the switching behavior.

II. EXPERIMENT

Barium ferrite thin films were rf sputtered onto single crystal [1 1 0] sapphire substrates, and then rapidly thermally annealed (RTA) at different temperatures and annealing times [3]. It was observed that the films were partially crystallized with various degrees of grain isolation, and therefore of grain interaction, as shown in Fig. 1.

The thermal activation volume V_{act} was determined from Eq. 1 [4], [5], using fluctuation fields H_f, which were in turn derived following $H_f=S/\chi_{irr}$, where the magnetic viscosity S and the irreversible susceptibility χ_{irr} from the DC demagnetization curves were measured using an alternating gradient magnetometer (AGM).

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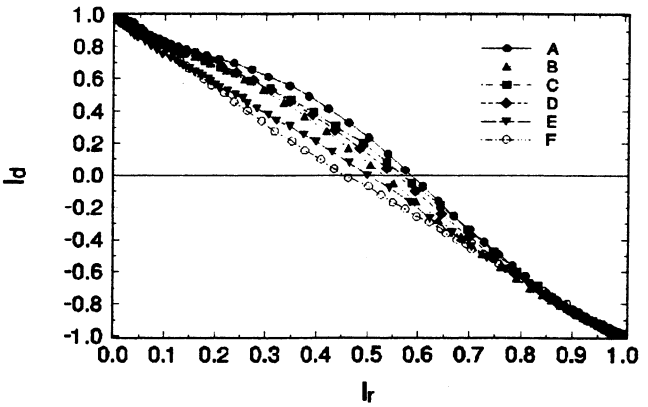

Fig. 1 Easy axes intergranular interaction as indicated by Henkel plot, or alternatively by ΔM plot as in Ref. 3.

$$V_{act} = \frac{k_B T}{M_s H_f} \tag{1}$$

The switching volume V_{sw} was obtained from the measurement of the time dependence of coercivity [6]:

$$H_c(t') = H_a \{1 - [\frac{k_B T}{K_u V_{sw}} \ln(\frac{At'}{0.693})]^{1/2}\} \tag{2}$$

where t' is the time taken to apply the reversing coercive field starting from zero field, and which was experimentally varied from about 1 s to over 1000 s. The fitting parameters V_{sw} and the anisotropy field H_a were determined by fitting the experimental data to Eq. 2. The values of K_u were derived from H_a by using the relation $H_a=2K_u/M_s$.

To verify these values, a third approach was used to independently determine H_f. In this approach the time t for the magnetization to decay to zero at an applied field in the vicinity of the coercivity was measured and used to calculate H_f (ΔH or "waiting time" measurement) [7]:

$$t = t_0 \exp(-\frac{H - H_0}{H_f}) \tag{3}$$

where H_0 is a reference field. From the linear regression slope of H vs. lnt, H_f and V_{act} were obtained without using χ_{irr}. The span of the "waiting time" t was from 0.2 s to over 1000 s. The same H and t may also be fitted to Eq. 2 as H_c and t' in order to determine V_{sw} since the zero magnetization point defines the coercivity at the zero-crossing time t [8].

The in-plane hysteresis loops were measured at various angles with respect to the magnetic easy axis direction using a vibrating sample magnetometer.

The microstructure of the films was studied using a Philips 420T transmission electron microscope (TEM).

III. Results

The peak values of S as shown in Fig. 2 and χ_{irr} were used to calculate H_f in Eq. 1. These peaks were found to occur at fields near the coercivities (See Table I). The values of H_f, which are in general field dependent quantities, were therefore only evaluated near the coercivities.

TABLE I
COERCIVITIES AND PEAK FIELDS ALONG EASY AXIS

Sample	H_c (Oe)	S_{max} (emu/cc)	χ_{irr}(max) (Oe^{-1} emu/cc)	$H(S_{max})$ (Oe)	$H(\chi_{irr}(max))$ (Oe)
A	3900	4.1	0.242	3750	3823
B	4455	5.6	0.232	4750	4590
C	4470	4.5	0.208	4750	4709
D	4700	7.2	0.278	4750	4833
E	5300	3.3	0.128	5750	5800
F	5400	0.9	0.033	5500	5560

The results for V_{act} and V_{sw} as listed in Table II showed that the values obtained from the "waiting time" measurement (see samples A*, B*, C*, D*, E*, F*) coincided with that from the viscosity and coercivity measurements, respectively.

The values of V_{act} and V_{sw} both increase with increasing grain interaction as indicated by the maximum values of ΔM in Fig. 3. While V_{sw} is about 4~5 times larger than the respective V_{act}, both are substantially smaller than the physical grain size (~8×10^{-16} cc) determined from a TEM micrograph in Fig. 4.

The in-plane angular dependence of the coercivities are shown in Fig. 5. The changes of H_c from the easy axes to the hard axes of all the samples were nonmonotonic. Peaks were usually observed at angles of about 70° from the easy axis.

TABLE II
ACTIVATION AND SWITCHING VOLUMES ALONG EASY AXIS

Sample	H_f (Oe)	V_{act} (10^{-18}cc)	V_{sw} (10^{-17}cc)	H_a (Oe)	K_u (10^5erg/cc)
A	16.8	6.48	2.79	4771	9.07
A*	19.5	5.6	2.89	4821	9.16
B	24.1	4.52	2.35	5520	10.5
B*	24.7	4.41	2.44	5499	10.5
C	21.6	5.04	2.43	5552	10.6
C*	22.3	4.88	2.57	5471	10.4
D	26	4.19	2.05	5867	11.2
D*	26	4.19	2.05	5849	11.1
E	25.8	4.22	2.10	6416	12.2
E*	26.3	4.14	2.23	6777	12.9
F	27.3	3.99	1.79	6979	13.3
F*	30.6	3.56	1.77	6965	13.2

* Results from ΔH or "waiting time" measurement

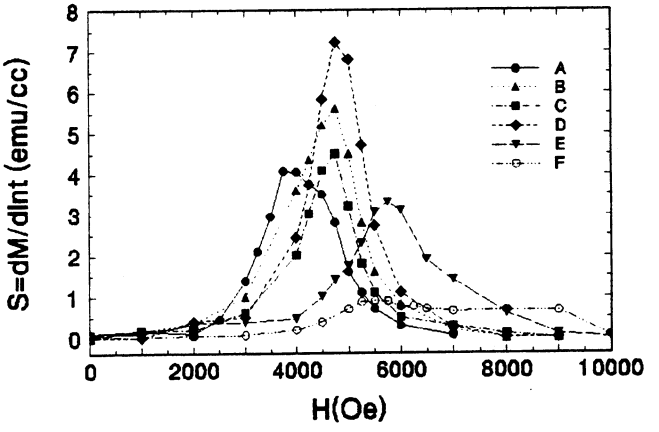

Fig. 2. Room temperature magnetic viscosity in the easy axis. The time window was from 0.2 s to 300 s.

IV. Discussion

From the bright field TEM image of sample B as shown in Fig. 4., it can be seen that the grains of the film are elongated in shape with average grain size of about 500x3000 Å., and well aligned with c-axis being parallel to the short axis of the elongated grains.

V_{sw} is defined as the volume of a switching unit during the magnetization reversal process. It is equal to the mean physical grain size if the grains are noninteracting single domain particles which undergo coherent rotation. V_{act} is defined as the volume of a thermal activation unit and is a field dependent quantity. Its value at the peaks of the magnetic quantities S and χ_{irr} usually does not reflect the physical grain size due to the distribution of both the grain size and the anisotropy energy.

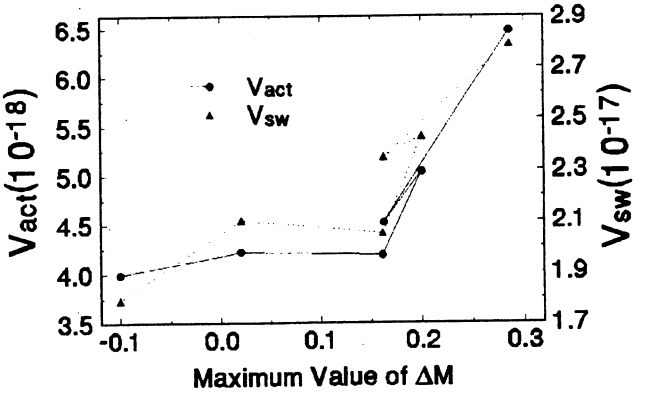

Fig. 3. V_{act} (from the viscosity measurements) and V_{sw} (from the coercivity measurements) of the samples.

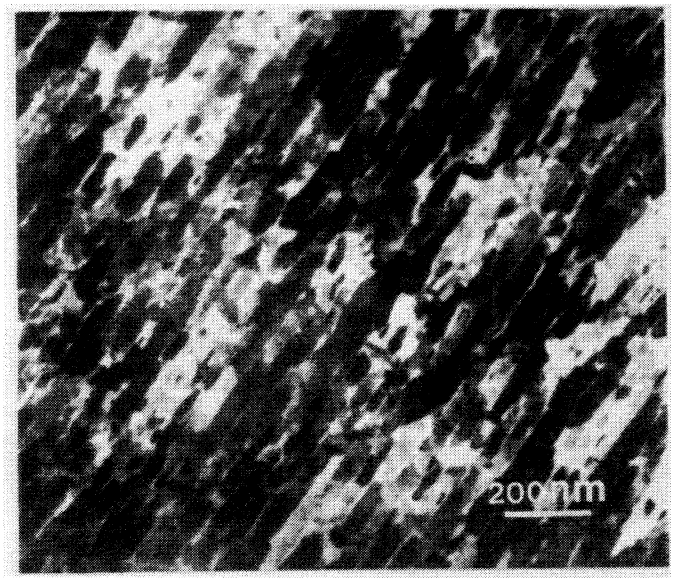

Fig. 4. TEM micrograph of sample B.

Intergranular interactions can increase the value of effective V_{sw} and V_{act}. This may cause the observed larger V_{act} and V_{sw} in samples with greater magnetostatic grain interaction as indicated in Fig. 3.

The inconsistencies between V_{act}, V_{sw} and the TEM grain size were found in barium ferrite and some other particulate media, and were commonly attributed to incoherent rotation [9, 10, 11]. The possibilities of various modes of incoherent rotation during the switching process in barium ferrite particles were also investigated theoretically [12, 13]. The nonmonotonic angular dependence of coercivity as indicated in Fig. 5 strongly suggests that some form of incoherent rotation is responsible for the switching [14], and results in the much smaller V_{act} or V_{sw} than the grain size.

Tobin et al [15] showed using a coherent rotation model that thermally activated magnetization reversal could cause a

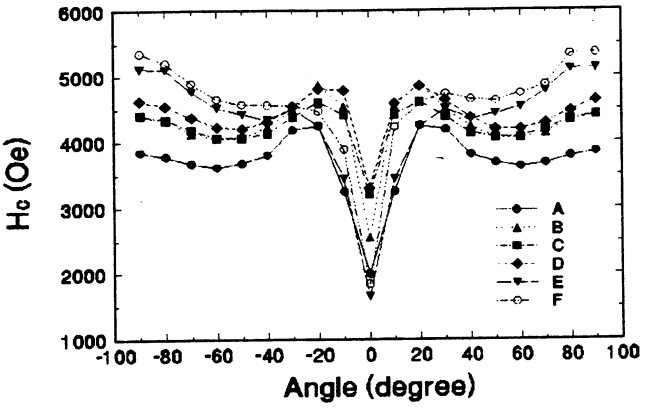

Fig. 5 In-plane angular dependence of coercivity. 0° is the hard axis direction, the easy axis is at ±90°.

small local maximum in coercivity at 60° to the easy axis at room temperature. In this model, H_c along the easy axis direction was still shown to be by far the largest. However, we believe that this coherent rotation model with thermal effects is not sufficient to account for the distinct nonmonotonic angular dependence of coercivity observed here, especially since the time dependence studies suggested $K_uV > 2x10^{-11}$ erg in all the samples, which is greater than the 10^{-11} erg assumed by Tobin. It was also found that the switching field along the hard axis was generally larger than that along the easy axis [3], which was inconsistent with the coherent rotation model.

V. Conclusion

The magnetic switching and thermal activation processes were studied in c-axis aligned barium ferrite thin films. Experimental evidence was found which links the incoherent rotation in magnetic switching to the commonly observed inconsistency between the activation volume and the switching volume with the physical grain size.

Acknowledgment

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