Magnetic viscosity and switching volumes of annealed Fe/Pt multilayers

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Magnetic viscosity and the phenomenon of the sweep-rate dependence of the coercivity are important for the characterization of magnetic recording media. The activation volume of magnetization reversal or switching volume is directly related to medium noise. The magnetic viscosity behavior of annealed Fe/Pt multilayers was studied and the switching volumes were obtained by both measurements of the sweep-rate dependence of coercivity and time dependence of magnetization. It is found that samples with larger coercivities have smaller switching volumes, and an estimate of the magnetic grain diameter is about 9 nm. The coercivity mechanisms are also discussed. © *1996 American Institute of Physics.* [S0021-8979(96)07808-8]

I. INTRODUCTION

Magnetic viscosity parameters are directly associated with the microscopic structure of materials and with the processes responsible for magnetization. The analysis of magnetic viscosity may allow a better understanding of magnetization reversal and coercivity mechanisms. For magnetic recording media, the activation volume of reversal or switching volume is an essential parameter which is related to the media noise. Previously, we have reported that annealed Fe/Pt multilayers with fct structure have large in-plane coercivities and fine grain sizes,[1] which suggests potential applications in future ultrahigh-density magnetic recording. In this work, we studied the magnetic viscosity properties and the switching volumes of the annealed Fe/Pt multilayers.

II. MAGNETIC VISCOSITY

The phenomenon of magnetic viscosity has its origins in thermal agitation of magnetic moment over energy barriers. In many materials it is found experimentally that

$$M(H,t)=M(H,t_0)-S(H)\ln(t),\qquad(1)$$

where $S(H)$ is the viscosity coefficient. According to Street and Woolley,[2]

$$S(H)=\chi_{\mathrm{irr}}(H)H_f(H),\qquad(2)$$

where χ_{irr} is the irreversible susceptibility characterizing the barrier hopping and H_f the fluctuation field which is defined by

$$H_f(H)=k_BT/[V^*(H)M_s],\qquad(3)$$

where $V^*(H)$ is the activation volume of reversal, k_BT the Boltzmann energy, and M_s the magnetic moment per unit volume.

Another aspect of the time-dependent behavior is the sweep-rate (dH_a/dt) dependence of the coercivity. Higher sweep-rate measurements generally give larger values of H_c than lower sweep-rate measurements. Under certain assumptions, the coercivity varies linearly with respect to $\ln(dH_a/dt)$:[3]

$$H_c=k_BT/(V^*M_s)[\ln(dH_a/dt)+\mathrm{const}].\qquad(4)$$

The activation volume V^* can be obtained from the slope of the $H_c\sim\ln(dH_a/dt)$ plot.

III. SAMPLES AND MEASUREMENTS

Fe/Pt multilayers were deposited by rf and dc sputtering on cover glasses and annealed at 300 °C for 30 min. The base pressure of the sputtering system was 2×10^{-7} Torr and the Ar pressure was 5 mTorr during deposition. All magnetic measurements were made using a Micromag-2900 alternating gradient force magnetometer. For each measurement of the time dependence of magnetization, the sample was initially saturated with a positive field of 10 kOe, and then a constant negative test field was applied. In order to obtain the $\chi_{\mathrm{irr}}(H)$ curves, the dc demagnetization (DCD) and the isothermal remanence magnetization (IRM) curves were measured.

IV. RESULTS AND DISCUSSIONS

A. Magnetic parameters

The hysteresis loops of the annealed Fe/Pt multilayers with different bilayer thickness (d_b) were measured with applied field in the film plane. All of the measured samples had the same composition and a total thickness of 150 Å. The magnetic parameters such as coercivity (H_c) and squareness (M_r/M_s) are listed in Table I. Rather square hysteresis loops have been obtained for all samples. The table also shows that the coercivities are strongly dependent on d_b, which will be discussed later.

Figure 1 shows the $\chi_{\mathrm{irr}}(H)$ curves of the examined samples, which were obtained by differentiating the DCD and IRM curves, respectively. According to O'Grady[4] and Donnet *et al.*,[5] the IRM differential (χ_{irr}^i) measures the distribution of energy barriers to wall motion; while the DCD differential (χ_{irr}^d) measures the energy barrier to domain nucleation in the first instance and then examines the mechanism by which reversal proceeds. Thus, both quantities provide direct information about magnetization reversal, and their relations to coercivity and activation volume will be discussed later.

B. Magnetic viscosity properties

1. Sweep rate dependence of H_c

Measurements of the coercivities as a function of sweep rates were carried out for samples A, B, C, and D with sweep rates varying from 10 to 1000 Oe/s. The results shown in

TABLE I. The magnetic parameters and switching volumes of the annealed Fe/Pt multilayers.

Samples[a]	A	B	C	D	E
d_b (Å)	15	30	37.5	50	75
H_c (Oe)[b]	934	2220	2560	3140	1140
M_r/M_s	0.85	0.89	0.87	0.87	0.85
$V^*(\times 10^{-18}$ cm^3)[c]	6.96	1.42	1.93	1.20	...
$V^*(H_c)(\times 10^{-18}$ cm^3)	2.03	1.51	1.33	1.25	2.42

[a]Samples are: A: (Fe 8.2 Å/Pt 6.8 Å)$_{10}$; B: (Fe 16.4 Å/Pt 13.6 Å)$_5$; C: (Fe 20.2 Å/Pt 17.3 Å)$_4$; D: (Fe 27.4 Å/Pt 22.6 Å)$_3$, and E: (Fe 40.4 Å/Pt 34.6 Å)$_2$. All samples are the same total thickness and were annealed at 300 °C for 30 min.
[b]H_c was measured at a sweep rate of 250 Oe/s.
[c]V^* was determined from the measurement of the sweep-rate dependence of coercivity.
[d]$V^*(H_c)$ is the switching volume when the applied field equals to H_c.

Fig. 2 are that H_c linearly depends on $\ln(dH_a/dt)$. So Eq. (4) can be applied to analyze the results and the switching volumes are obtained, as listed in Table I. A small switching volume of 1.2×10^{-18} cm^3 has been measured for sample D which has a coercivity of 3.14 kOe. As the total film thickness h is 150 Å, the magnetic grain size which is defined as $(V^*/h)^{1/2}$ is about 90 Å.

2. Time dependence of magnetization

Logarithmic time decays have been observed for all samples under constant negative applied fields. As an ex-

ample, Fig. 3 shows the magnetization varying linearly with $\ln(t)$ for sample C under different applied fields. From these plots the viscosity coefficients $S(H)$ were obtained, as shown in Fig. 4. The variation of S with H essentially mirrors the behavior of $\chi_{\rm irr}(H)$ which gives a measure of irreversible processes in the film.

From $S(H)$ and $\chi_{\rm irr}(H)$, $V^*(H)$ can be obtained, as shown in Fig. 5. Clearly, $V^*(H)$ is not a constant. It depends on the applied fields. This arises from the fact that the applied field may affect both the height and the distribution of energy barriers. In the low-field region, both A and E have much larger V^* than the other samples, while in the high-field region, all samples tend to have the same V^*. At each sample's coercive field, the sample with larger H_c shows smaller $V^*(H_c)$. The values of $V^*(H_c)$ are matched very well with V^* obtained from the sweep-rate dependence measurement of coercivity except for sample A, for which V^* is a little larger than $V^*(H_c)$.

Both H_c and V^* are related to the magnetization reversal mechanisms which depend on the microstructure. Figure 1 reflects how the distribution of energy barriers varies with d_b. In the low-field region, for samples A and E, the nucleation field is greater than the domain-wall-pinning field as can be seen from the $\chi_{\rm irr}(H)$ curves. Hence, following the
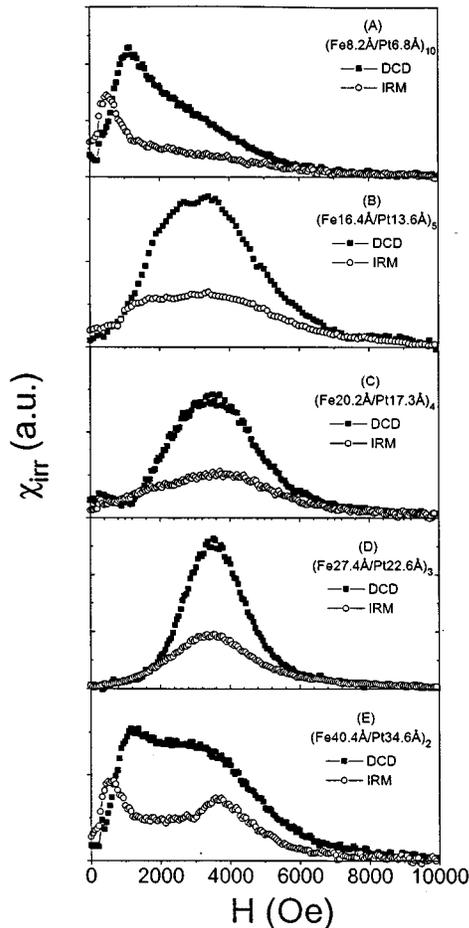

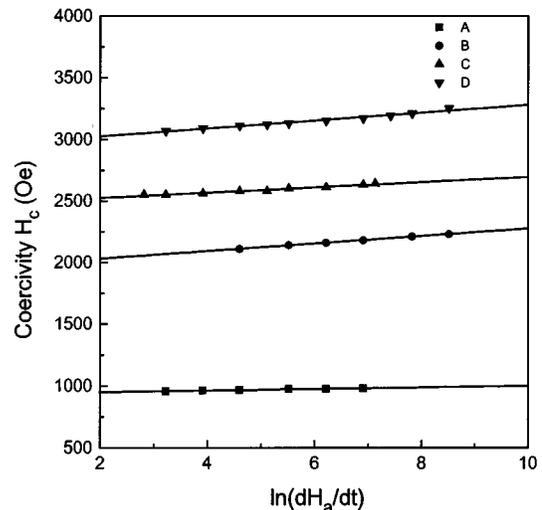FIG. 1. Differentiated remanence curves for annealed Fe/Pt multilayers.

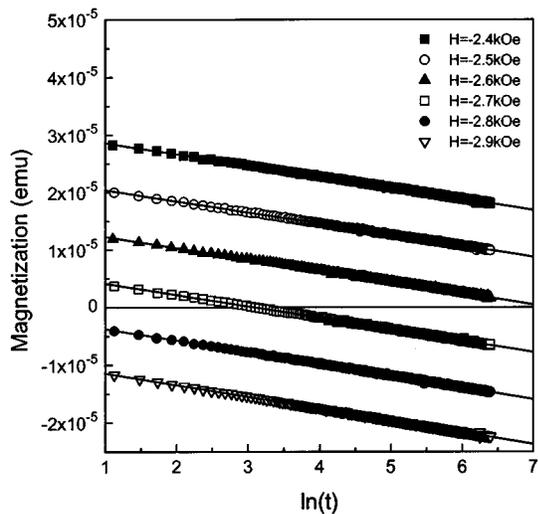FIG. 2. The variation of H_c with sweep rate dH_a/dt.

FIG. 3. Time decay of magnetization in the presence of constant magnetic fields in the direction opposite to the initial magnetization for sample C.

FIG. 5. The variation of activation volumes with applied field.

analysis of O'Grady,[4] once the domain is nucleated it expands quickly, causing a sharp increase in switching volumes. And then the decrease of activation volume with applied field may be associated with the pinning of the movement of the nucleated domain walls.

The coercivity is also related to the exchange coupling between grains. Generally the coercivity increases with the reduction of exchange coupling.[6] For a system without interaction, χ_{irr}^d and χ_{irr}^i should be identical with $\chi_{irr}^d = 2\chi_{irr}^i$. This suggests that the grains are more strongly exchange coupled for samples A and E, for which the χ_{irr}^i curves increase at lower field than the χ_{irr}^d curves.[7] The exchange coupling ap-
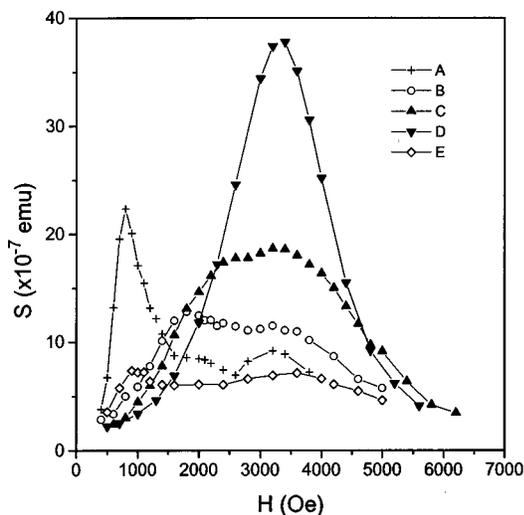
pears to be reduced for samples B, C, and D as the $\chi_{irr}^i(H)$ and $\chi_{irr}^d(H)$ curves are centered at the same position. High-resolution transmission electron microscopy (TEM) data on these samples show grain sizes of about 15 nm. The large value of H_c in sample D presumably is connected with a smaller exchange coupling, but the correlation of this with details of the nanostructures awaits further TEM studies.

V. SUMMARY

Through the study of magnetic viscosity behavior of the annealed Fe/Pt multilayers, their activation volumes of reversal were obtained. Films with larger coercivities have smaller switching volumes. Given the small estimated value of the magnetic grain size (~ 90 Å) and the large and controllable coercivities, these films may have potential as new ultra-high-density recording media.

ACKNOWLEDGMENTS

FIG. 4. The variation of viscosity coefficient S with applied field H.

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