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Article *in* Journal of Applied Physics · May 1996

DOI: 10.1063/1.362222 · Source: IEEE Xplore

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AIP | Journal of Applied Physics

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Citation: J. Appl. Phys. **79**, 5700 (1996); doi: 10.1063/1.362222
View online: http://dx.doi.org/10.1063/1.362222
View Table of Contents: http://jap.aip.org/resource/1/JAPIAU/v79/i8
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A dynamic study of domain formation mechanism during thermomagnetic recording based on micro-Hall effect measurements

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A method for analyzing the dynamics of domain formation during the thermomagnetic recording process has been developed based on the extraordinary Hall effect.[1,2] A magnetic domain is written at the center of a cross-shaped magneto-optical sample having an area of 5×5 μm^2, and the Hall voltage is monitored during the recording process. As far as domain nucleation is concerned, we find that the temperature gradient around the transition region (i.e., the region whose temperature is between the critical temperature for magnetization reversal and the Curie point) is very important. Under the conditions of high power and short pulse-width laser, a domain can form only during the cooling period. However, it is possible for a domain to form during the heating cycle under a low power, long pulse laser beam. © *1996 American Institute of Physics.* [S0021-8979(96)06108-1]

I. INTRODUCTION

In thermomagnetic recording, a focused laser beam creates a hot spot in a thin magnetic film, thus allowing an external magnetic field to reverse the direction of local magnetization. This is a very complex dynamic phenomenon involving the nucleation of one or more domains, followed by domain expansion and/or contraction.[3] The details of this process depend on the recording conditions and the composition of the recording material. To enhance recording density, one must write domains as small as possible under the constraint of an acceptable signal-to-noise ratio in readout. To achieve this goal, one may reduce the laser wavelength and increase the numerical aperture of the objective lens in order to attain a small, diffraction-limited focused spot. Alternatively, one might strive to develop a technique that allows the writing of small domains even when the focused light spot is not as small. In the latter case, the mechanism of domain formation will have to be better understood, and the most suitable combination of material properties and recording conditions must be adopted. For example, we have observed that under certain conditions the newly formed domains shrink during the cooling cycle. In such cases, the small size of the final domain might be misleading, since it may have damaged an adjacent domain while it was being recorded. Because the existing "static" methods of domain observation and measurement monitor only the final state of a recorded domain, they are incapable of providing insight into problems that are of a "dynamic" nature. On the other hand, dynamic measurement techniques, such as the one described in this article, are quite attractive since they enable the sensing and monitoring of a domain while it is being written.

In this article, we describe a micro-Hall effect measurement scheme for the study of domain formation mechanism. The Hall voltage is proportional to the instantaneous average magnetic moment within the measured area of the sample. By monitoring the Hall signal during thermomagnetic recording, we observe the process of domain formation in real time.

II. EXPERIMENTAL SETUP

A schematic diagram of the experimental setup is shown in Fig. 1(a). The laser beam is focused at the center of the magneto-optical (MO) sample, and a perpendicular magnetic field is applied by a small coil having a diameter of 2 mm. The maximum available field is 750 Oe, which corresponds to a current of 2.5 A through the coil. In order to monitor the variations of Hall voltage caused by the formation of a single domain, a cross-shaped sample, shown in Fig. 1(b), was prepared. The central part of the cross, which has an area of 5×5 μm^2, is made of TbFeCo film. Two different magnetic

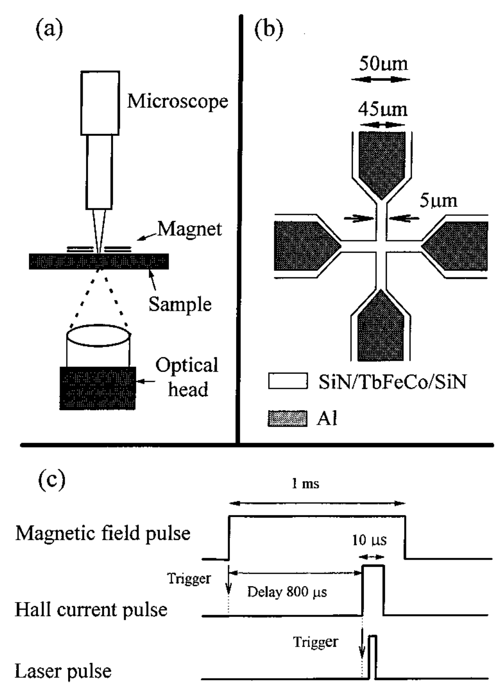

FIG. 1. (a) Schematic diagram showing the experimental setup for micro-Hall effect measurements. (b) Cross-shaped sample used in the experiments. (c) Temporal relationship among the magnetic field pulse, the Hall current pulse, and the laser pulse.

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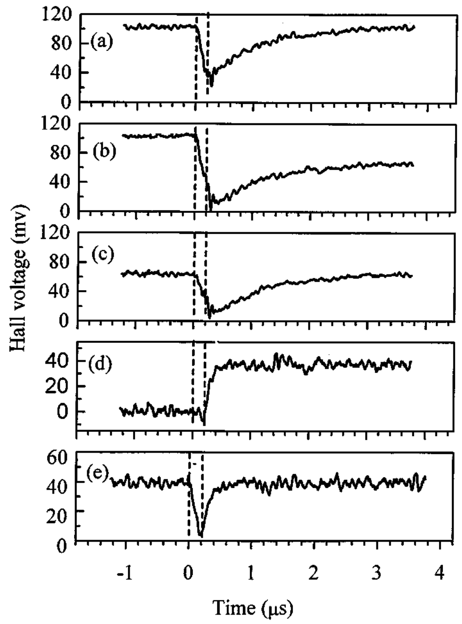

FIG. 2. Hall signals for a Fe-rich sample obtained in several kinds of measurements with a laser pulse having $P=8$ MW and $T=200$ ns. (a) In the presence of a $+750$ Oe field along the direction of initial magnetization, no domain is being formed. (b) Domain-writing signal in the presence of a -300 Oe field. (c) Domain-rewriting signal under $H=-300$ Oe. (d) The difference between signals shown in (a) and (b), containing information about magnetization reversal. (e) The difference between signals shown in (a) and (c).

films were used in our studies. Sample 1 had a thickness of $\delta=25$ nm, coercivity $H_c \geqslant 25$ kOe at room temperature, and Curie and compensation point temperatures of $T_c=230$ °C and $T_{comp}=-50$ °C, respectively. Sample 2 had $\delta=100$ nm, $T_c=260$ °C, $T_{comp}=190$ °C, and $H_c=5$ kOe. The results presented in Secs. III A and III B were obtained using sample 1, while those in Sec. III C correspond to sample 2. In both samples, the magnetic film was sandwiched between a 75 nm thick SiN underlayer and a 200 nm thick SiN overlayer. The four aluminum electrodes, having a thickness of 300 nm each, were connected to the four sides of the MO film. The Hall signal was measured using the four-point probe method. The magnitudes of the applied magnetic field H, the laser power P, and the laser pulse duration T were all adjustable. Temporal relations among the magnetic field pulse, the Hall current pulse, and the laser current pulse are shown in Fig. 1(c). The Hall current pulse has been delayed by 800 μs in order to avoid perturbations caused by the induced voltage from the magnetic field pulse.

III. RESULTS AND DISCUSSION

A. Recording with a short laser pulse

Here the laser power $P=8$ MW and its pulse width $T=200$ ns. One set of our measurement results is shown in Fig. 2. In Fig. 2(a) the laser pulse is turned on, but no domain is being formed. For this measurement, we saturate the magnetic moment of the sample in the $+Z$ direction, and maintain a $+750$ Oe field on the sample in order to prevent domain formation during the experiment. The vertical dash lines in Fig. 2 show the duration of the laser pulse. The laser creates a time-dependent temperature profile in the film. We define the Curie disk as the region where at any given instant of time the temperature is higher than the Curie temperature. In the early stages of heating, the radius of the Curie disk is zero, but once formed, it rapidly increases with time. The Hall signal drops quickly during the heating cycle because the magnetization decreases with the rising of temperature. Once the laser is turned off, the signal gradually returns to its original level. In Fig. 2(b) a domain is being written in the presence of a -300 Oe field. The signal in this case also decreases when the laser is first turned on, but it does not return to the original level since a domain is now formed in the region of the hot spot. The voltage difference between the initial and final levels is proportional to the size of the written domain. Figure 2(c) represents the case of domain rewriting. Following the writing of a domain, we turn on the laser once again with the same power and pulse duration, and without changing the magnetic field. Observe that the initial signal level in Fig. 2(c) is the same as the final level in Fig. 2(b). During the heating period the signal decreases, but it recovers to its original level after cooldown. This indicates that the size of the domain remains the same after rewriting.

Variations of the Hall voltage with time shown in Fig. 2(b) are caused both by the variations of the magnitude of magnetization due to the temperature change, and by the formation of a reverse domain after a certain point in time. To obtain the signal caused by magnetization reversal alone, we subtract the signal in Fig. 2(a) from that in Fig. 2(b) and refer to the difference, shown in Fig. 2(d), as the differential writing signal. This differential Hall signal indicates that the signal arising from domain formation does not have any significant value until after the laser has been turned off. Under these recording conditions, therefore, domain formation must occur during the cooling period. The reason for this behavior may be speculated to be as follows. The temperature of the region in which the domain nucleates should be greater than some critical temperature, T_{crit}, which is a function of the strength of the applied magnetic field H, and is lower than the Curie temperature. We define the region in which the temperature is higher than T_{crit} as the critical disk. By definition, the critical disk is always greater than the Curie disk. A domain can form only in the annular region between the Curie disk and the critical disk. If the temperature gradient is so large that this annular region is narrower than the width of a magnetic domain wall, then no domains can form. In the cooling process, however, temperature gradients are on the decline, and nucleation should occur more readily.

Figure 2(e) shows the difference between the signals in Figs. 2(a) and 2(c). Observe that, in the rewriting process, the signal arising from the reversed domain reaches a minimum and then returns to its initial value. The nonzero value of the minimum signal in this case indicates that a certain part of the domain survives during the heating period.

B. Recording with a long laser pulse

The pulse width T used in this case was 1 μs, and the applied magnetic field H was -450 Oe. Figures 3(a)–3(c) show the differential writing signals during recording experi-

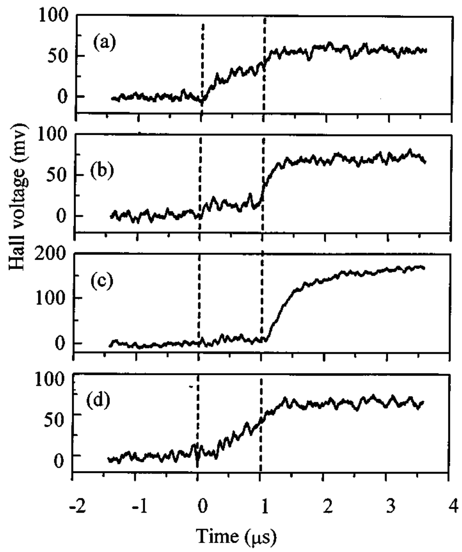

FIG. 3. Differential writing Hall signals for a Fe-rich sample obtained during recording with a $T=1$ μs laser pulse and in the presence of a magnetic field $H=-450$ Oe. (a) $P=1$ MW; the domain is formed early in the heating cycle. (b) $P=2$ MW; the domain signal during the heating period is smaller than that in (a) due to the higher temperature levels. (c) $P=5$ MW; the domain no longer forms during the heating cycle. (d) $P=5$ MW, but the laser is slightly out of focus. In the first 300 ns, no region of the MO film reaches T_{crit}. After that, the critical disk is formed and expands rapidly.

ments corresponding to laser power levels of $p=1$, 2, and 5 MW, respectively. In Fig. 3(a), we observe that a domain forms in the beginning of the heating period and that it continues to grow afterwards. This result can be explained as follows. Because of the low level of laser power being used, it takes the magnetic film a long time to reach the Curie temperature. But, during this period, heat diffusion broadens the temperature profile. The time duration in which the Hall signal increases rapidly corresponds to a rapidly expanding critical disk. In Fig. 3(b) essentially the same phenomena occur, but the signal during the heating cycle is smaller than that in Fig. 3(a). This is due to the fact that the magnetization decreases with a rising temperature. In Fig. 3(c), the domain differential writing signal does not have a significant value before the laser is turned off. This is similar to the behavior described in Sec. III A in conjunction with a short laser pulse. Note in Fig. 3 that the final domain size is increasing with the increase of the laser power. Figure 3(d) shows the Hall signal during writing under the same conditions as in Fig. 3(c) except for a slight defocusing of the laser beam. This figure indicates that the domain has formed during the heating cycle. The reason for this behavior is that, as a result of defocusing, the temperature profile has broadened.

C. Domain size variations during the cooling period

In this section, the Tb-rich samples are measured. As in the preceding experiments, the saturated state of the magnetization is along the $+Z$ direction. Figure 4 shows the differ-

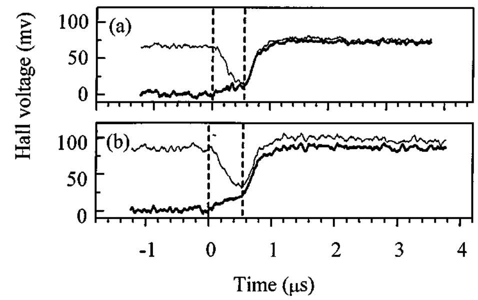

FIG. 4. Differential writing (dark) and rewriting (light) signals for a Tb-rich sample in the presence of two different magnetic fields. (a) With $H=+300$ Oe the domain shrinks somewhat during cooling. (b) With $H=+600$ Oe, the domain does not shrink during writing, but expands during rewriting.

ential writing and rewriting signals for two different magnetic fields when the laser pulse width $T=530$ ns and the laser power $P=9.3$ MW. The heavy curves show the differential writing signals, while the light curves are the differential rewriting signals. In both cases, the level of the rewriting signal immediately after heating is greater than its initial level. This indicates that the written domain expands somewhat during rewriting. In Fig. 4(a), where $H=+300$ Oe, the writing signal slowly decreases after reaching a maximum value. The fact that the initial level of the rewriting signal is below the maximum value of the writing signal indicates a shrinkage of the recorded domain during the cooling cycle. In case Fig. 4(b), where $H=+600$ Oe, the domain does not shrink significantly during the cooling phase of the writing process. This is due to the presence of a stronger magnetic field in this case compared to Fig. 4(a). The strong magnetic field in Fig. 4(b) also causes the domain to expand during rewriting.

IV. CONCLUDING REMARKS

From the type of measurement described in this article, in addition to the above information, one can reconstruct the temperature profile within the sample by employing the known dependence of magnetization on temperature. This is a helpful step in furthering our understanding of the recording mechanism. We will concentrate on studying the measurements of the thermal constants of MO media in the future.

ACKNOWLEDGMENTS

The authors thank Junko Ushiyama of the Hitachi Central Research Laboratory for preparing the samples, and Warren Bletscher of the Optical Sciences Center for design and construction of the electronic subsystem.

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