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STUDY OF DOMAIN FORMATION MECHANISM IN MAGNETO-OPTICAL MATERIALS USING MICRO HALL EFFECT MEASUREMENTS

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Abstract - A method for analyzing the dynamics of domain formation in magneto-optical recording media was established using measurement of the extraordinary Hall effect. A magnetic domain was written on a cross-shaped magneto-optical film having an area of 3.4x3.4 μm^2 at the center of the cross, and the extraordinary Hall voltage was monitored during thermomagnetic writing. Two kinds of TbFeCo films were investigated. For RE-rich film, the nucleated domain expands with the expanding Curie disk in the heating process, and then shrinks in the cooling process. For TM-rich film, on the other hand, the domain cannot follow the Curie disk and, therefore, does not appear during the heating process. The domain in this case is formed in the cooling process and does not show any tendency to shrink.
KEYWORDS: Extraordinary Hall Effect, Domain Formation, Thermomagnetic Writing

INTRODUCTION

The second generation magneto-optical (MO) disk has recently been introduced in the market. Although the recording density is twice that of the first generation disks, it is still less than 1Gb/in^2. The present densities are comparable with those of conventional magnetic disks available nowadays, so the advantage of MO disk is missing. Moreover, it has been estimated that for a moving-image recording media a density in excess of 3Gb/in^2 is required. Therefore, to extend the range of applications of MO disks, it is essential to increase the recording density by substantial amounts.

As high density readout techniques, the use of short wavelength (blue-green) lasers, optical super-resolution, and magnetic super-resolution have been proposed and investigated. These techniques, however, do not provide a solution to the problem of high density writing. In any event, writing of small domains with a relatively large light spot will have to be performed in the near future. Up to now, the diameter of written domains has been about one half of the focused light spot diameter. In the future, however, domain diameters as small as 1/3 or even 1/4 of the light spot must be written. To achieve this goal, the domain formation mechanism must be clearly understood, and the most suitable media must be identified. As an example of important phenomena that need to be investigated in this context, we mention the detection of domain wall motion during thermomagnetic writing. Recently, Du and Kryder reported the relationship between domain wall mobility and compensation temperature on RE-TM films measured using a high speed polarized light microscope with stroboscopy [1].

In the present study, we have used a micro-Hall effect measurement device to detect domain nucleation and wall motion during thermomagnetic writing. Micro-Hall probes are well known for measurements of the magnetic field distribution [2]. More recently, Webb has proposed to use micro-Hall effect techniques for dynamic measurements of domain nucleation and wall motion, because the change of the extraordinary Hall voltage corresponding to the change of domain size can be measured in real-time [3]. This method has the advantage that its resolution can be increased by reducing the size of the Hall element, and in this respect it is superior to techniques based on optical microscopy.

EXPERIMENTAL

Sample Preparation

Our samples have a cross-shaped geometry, which was patterned by photolithography, as shown in Fig.1. The central part of the cross is made of TbFeCo film with a thickness of 100 nm, sandwiched between 75 nm thick SiN underlayer and 200 nm thick SiN overlayer. The four electrodes are made of aluminum film with a thickness of 300 nm. Within the central part of the cross, which has an area of 3.4 x 3.4 μm^2, a domain is written using an optical head with 780 nm laser diode and a NA=0.55 objective lens through the 1.2mm-thick glass substrate of the sample.

Two kinds of TbFeCo film were prepared for these studies. The temperature dependences of the saturation magnetization M_s for these two films are shown in Fig.2. Both films have the same Curie temperature of 260 °C, but their compensation temperatures T_{comp} are different. For the RE-rich film T_{comp} = 190 °C, while for the TM-rich film T_{comp} is below room temperature. Coercivity at room temperature is 5 kOe for the RE-rich film, and 10 kOe for the TM-rich film. We had two RE-rich samples

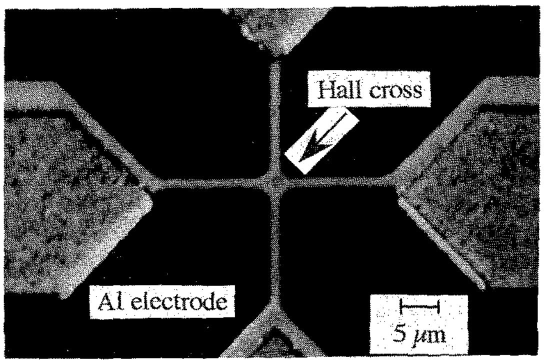

Fig.1 Micro-Hall element and aluminum electrodes.

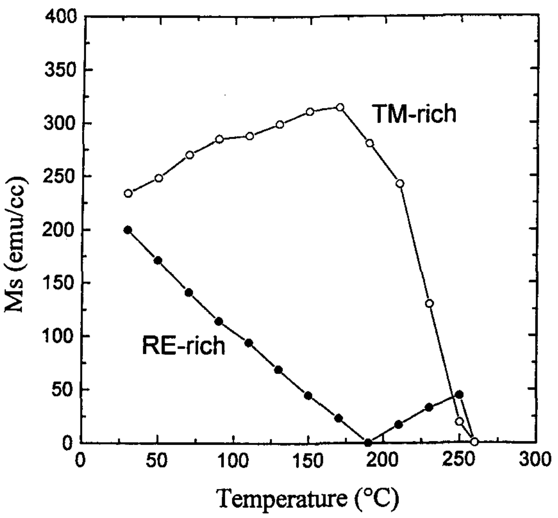

Fig.2 Temperature dependence of saturation magnetization M_s for two TbFeCo films.

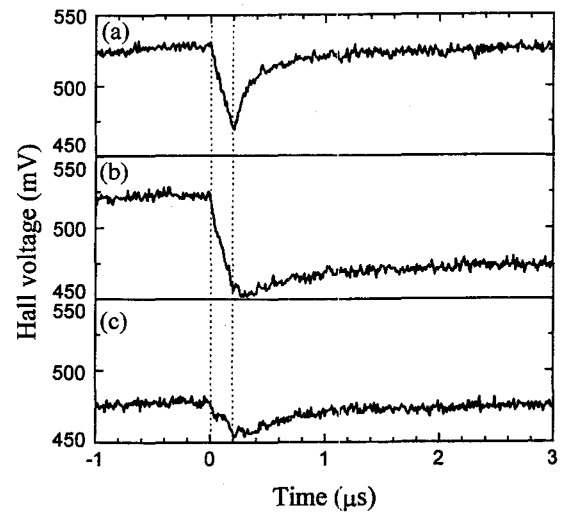

Fig.3 Hall voltage in three processes, (a) no domain, (b) domain writing, and (c) repeat writing, for RE-rich film. Laser pulse is 8 mW and 200 ns.

with nearly identical composition and structure and, similarly, two TM-rich samples. The measurement results reported here were the same for the two samples in each pair.

Hall Voltage Measurement

When a reverse circular domain with radius r is formed in the center of the cross-shaped Hall element, which has area S, the change of the Hall voltage ΔV_H (relative to the saturated state) is proportional to the change of the average magnetization inside the cross, that is,

$$\Delta V_H = 2 \cdot \frac{I}{d} R_H \cdot f_s \cdot \mu_0 M_s \cdot \frac{\pi r^2}{S}$$

In the above equation, d is the thickness of the film, I is the electric current, R_H is the resistivity factor for the extraordinary Hall coefficient, (for RE-TM alloy films R_H depends on TM magnetization only), f_s is the sensitivity function [3] and M_s is the saturation magnetization. (The magnetization is assumed to be saturated in the perpendicular direction.) By monitoring the Hall voltage during the thermomagnetic writing and/or erasure process, the change in the domain radius can be measured in real time.

The Hall voltage is measured using the four-point probe method. For the electrical current, we selected an amplitude of 900 μA and a pulse width of 10 μs to avoid overheating the sample. The magnetic field was produced by a small coil which could produce 300 Oe for each ampere of current. The coil was pulsed with a pulse width of 1ms. To detect the small Hall effect signal (of the order of micro-volt), we used an amplifier with a gain of 500 and a digitizing oscilloscope. The sampling interval for this oscilloscope was 5 ns.

RESULTS AND DISCUSSION

Signals of Thermomagnetic Writing

Figure 3 shows an example of the measured Hall voltage for a RE-rich film in three processes: (a) light pulse irradiation without domain formation, (b) domain writing, and (c) domain repeat writing. (The difference between writing and repeat writing is that in the first case the sample is initially saturated, while in the second case a domain is already written at the center of the sample. Everything else such as the laser pulse, the applied magnetic field, the position of the sample, the Hall current, etc., is exactly the same in the two experiment.) The laser pulse is 8 mW and 200 ns, and each plot was obtained by repeating and averaging 16 measurements. Figure 3(a) shows the Hall voltage V_H in the absence of domain formation. The external field is -700 Oe, preventing the formation of the domain. The origin of the horizontal axis (i.e., Time = 0) denotes the start of the light pulse. V_H decreases with increasing temperature due to the temperature dependence of TM subnetwork magnetization, and returns to the initial value after irradiation is stopped. Figure 3(b) shows the signal in the case where domain is being written. The magnetic field is now +500 Oe. V_H decreases and no longer returns to the initial value. This indicates that a domain has been formed. Figure 3(c) shows the case where the domain recorded in (b) is repeat written under the same condition as in Fig.3(b). V_H starts at a low level corresponding to the final value of V_H in Fig.3(b), reaches a minimum, and then returns to the same initial value. This indicates that the temperature (and perhaps the domain size) changes during repeat writing but, at the end, the domain returns to its initial size. This measurement is useful since, as we shall see, it can indicate whether or not the domain disappears in the heating process.

To study the domain formation process during thermomagnetic writing, it is necessary to separate the signal due to domain formation from that caused by the change of temperature. Figure 4(a) shows the voltage difference between the case where no domain is formed (Fig.3(a)) and the case where domain is written (Fig.3(b)). The thick curve is the result obtained by smoothing the data. This voltage difference is twice the signal coming from the reverse-magnetized region of the sample. For example, in the case where a domain is formed and a Curie

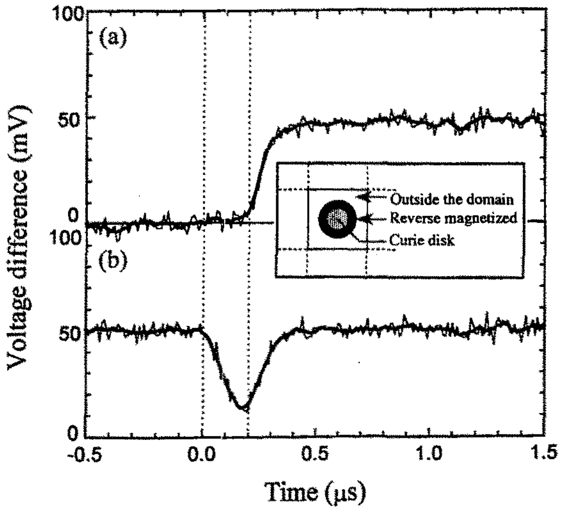

Fig.4 Voltage difference between the case where no domain is formed and the cases where a domain is being written (a) and a domain is being repeat written (b).

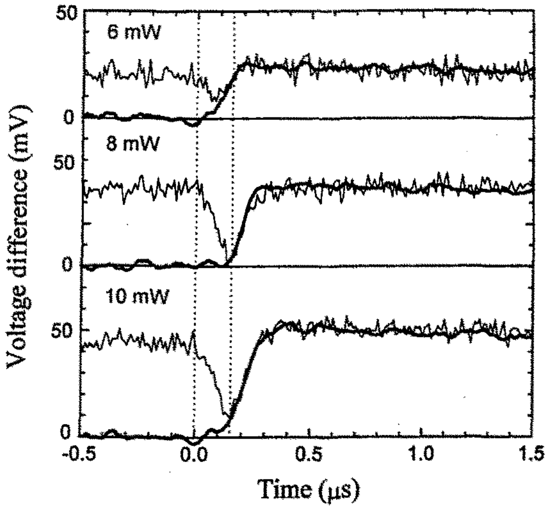

Fig.5 Voltage difference of RE-rich film for several laser powers. The pulse width is 150 ns and the magnetic field is 500 Oe. Note that the final domain becomes larger as the laser power is increased (Dark curve = domain writing, Light curve = repeat writing).

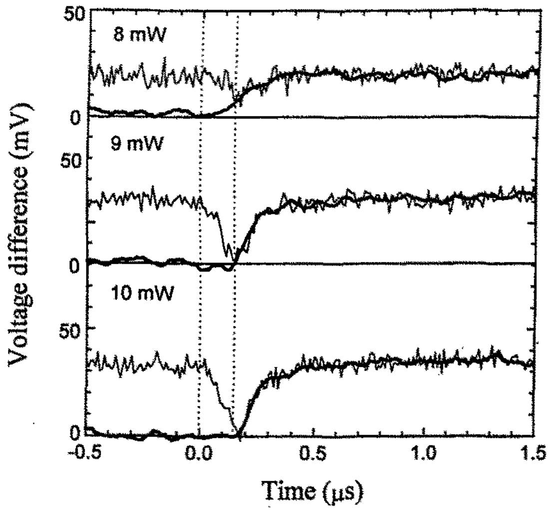

Fig.6 Voltage difference of TM-rich film for several laser powers. The pulse width is 150 ns and the magnetic field is 500 Oe (Dark curve = domain writing, Light curve = repeat writing).

disk (i.e., the region where the temperature is above the Curie point) appears inside the domain, as in the inset of Fig.4, the signals from the Curie disk and from the outside region of the domain are suppressed by this subtraction, but the signal from the ring shaped domain not only survives, but is also multiplied by a factor of two. For this difference signal, the time at which the value of the signal becomes non-zero indicates the beginning of domain formation.

In Fig.4(a), the signal increases gradually after the start of the laser pulse and it rises steeply towards the saturated value right after the end of the pulse (i.e., at t = 200 ns). This behavior may be (although not convincingly) indicative of the fact that the domain is nucleated and expands in the heating process. However, the signal does not increase rapidly, because a Curie disk appears and the reverse-magnetized region shrinks in size. After the end of the laser pulse, the signal increases rapidly with decreasing temperature, reaching saturation in approximately 200 ns.

Figure 4(b) shows the voltage difference between the case where no domain is formed (Fig.3(a)) and the case where an already recorded domain is repeat written (Fig.3(c)). The signal starts at the same level as the saturated value in Fig.4(a), reaches a minimum, and then returns to its initial value. The non-zero minimum of this signal indicates that a certain fraction of the original domain survives even when the temperature reaches its maximum, that is, the domain does not disappear in the heating process. (Remember that the difference signal is proportional to the signal coming from the reversed region.)

Domain Formation Process

Two kinds of TbFeCo films were investigated under various writing conditions. Figure 5 shows the voltage difference signals for several laser powers for RE-rich film. The pulse width is 150 ns and the external field is 500 Oe. The domain-writing signal is shown by smoothed data (thick curve), and the repeat writing signal is shown by the thin curve. At 6 mW, the domain is nucleated right after the start of the laser pulse. However, at 8 mW, the domain does not appear to have formed in the heating process, because the domain-writing signal remains almost zero until t = 150 ns. (Also, the repeat writing signal becomes zero at 150 ns.) From these observations, it seems that the Curie disk grows faster than any possibly nucleated domain could have grown and, therefore, no domain is formed in the heating process. However, at 10 mW laser power the domain appears once again in the heating process. This result might seem counterintuitive, in that if the Curie disk grows faster than the domain at 8 mw, then the same thing must also occur at higher laser power. But apparently the temperature gradient and the domain wall mobility at elevated temperatures conspire to create a domain early on and expand it beyond the reach of the Curie disk in the case of 10 mW laser pulse.

The case of TM-rich film is shown in Fig.6, where it is

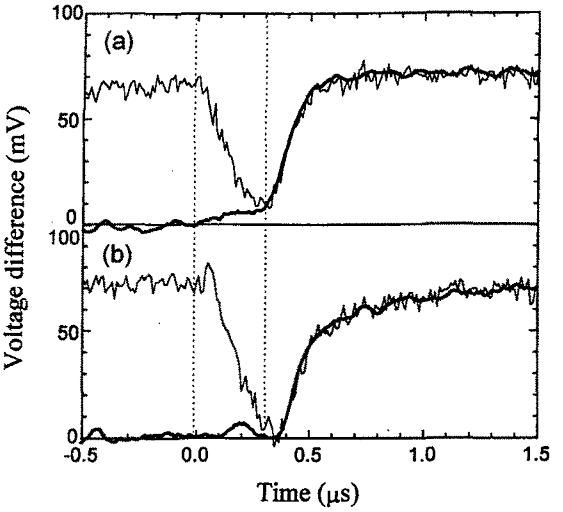

Fig.7 Voltage difference signals from (a) RE-rich film (8mW) and (b) TM-rich film (9mW) for the pulse width of 300 ns. The magnetic field is 500 Oe.

observed that at 8 mW the domain is formed during the heating process (the domain cannot be written at or below 6mW), whereas at 9 mW and 10 mW the domain is formed during the cooling process. Therefore, the argument that the Curie disk overtakes the domain during heating is more consistent for TM-rich film.

The behavior of the domain in the heating process can be seen more clearly for longer laser pulse. Figure 7 shows voltage difference signals for the pulse width of 300 ns, where the laser power is 8 mW for RE-rich film (a) and 9 mW for TM-rich film (b). For RE-rich film, the domain-writing signal increases monotonically after the start of the laser pulse and rises to the saturated value after the end of the pulse. On the other hand, for TM-rich film, the signal first reaches a maximum and then decreases to zero at the peak temperature, before increasing again with decreasing temperature. These results indicate that, in the heating process, the domain of RE-rich film survives and expands with the expanding Curie disk. The domain probably becomes ring shaped with a narrow width surrounding the Curie disk, but it does not disappear. In the case of TM-rich film, the domain cannot follow the Curie disk during the heating process and, at last, it is consumed by the Curie disk.

Until now we have focused on the heating process, and hereafter, we are going to discuss the cooling process. In Fig.5, it can be seen that at 10 mW the domain-writing signal reaches a maximum value before it decreases to the saturated level. Moreover, it can be seen that for repeat writing at 10 mW the peak signal value reached after the end of the pulse is larger than that before the pulse. These results indicate that the domain within the RE-rich film shrinks in the cooling process. The degree of shrinkage of the domain increases with increasing laser power and/or with decreasing pulse width, that is, shrinkage is related to temperature gradient.

The reason for the observed differences in the domain formation process between RE-rich film and TM-rich film is not yet clear. It is generally believed that domain nucleation is dominant in RE-rich film, while domain wall motion is dominant in TM-rich film. Considering this point, it can be understood that the nucleation of nano-scale domains is faster than the movement of the domain wall, and thus only in RE-rich film can the domain follow the change of temperature and stay ahead of the Curie disk.

CONCLUDING REMARKS

It is generally believed that for TM-rich film the dependence of domain size on the laser power is strong, and that small domains are difficult to form. The conclusion is that RE-rich film is better for high density recording applications. However, our analysis of the Hall effect signal during writing indicates that domain shrinkage occurs on RE-rich film and this is probably the reason behind the weaker laser power dependence of the domain size in these media. For high-density recording the domain must not shrink, because, prior to shrinking, the domain might destroy or partially erase an adjacent domain. From this view point, RE-rich film investigated here may not be suitable. On the other hand, for TM-rich film the domain size is decided only by temperature (i.e., by the Curie disk) and so it can be controlled easily. Therefore, to achieve very high density recording, it might be better to use TM-rich film and to have some kind of structure on the substrate to restrict the spread of temperature or the expansion of the domain.

In this study, we have investigated only two kinds of films and it was only understood that the wall motion type of material seems to be suitable for high density recording. In order to select the most suitable film, we must study the dependence of domain formation process on compensation temperature, film thickness, and other compositions such as Gd-based or Dy-based film. Moreover, it remains to be clarified whether the type of domain formation, namely, nucleation type versus wall motion type, actually decides the outcome of the thermomagnetic cycle.

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