Magneto-optical recording on patterned substrates (invited)

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Patterning of glass or plastic substrates in the form of shallow square patches is a promising method of increasing the storage density for magneto-optical disks. The sidewalls of the patches pin the reverse-magnetized domains that develop in these samples. Confinement of domains within the patch boundaries during thermomagnetic recording has also been demonstrated. We have measured polarization conversion of the incident light on the sidewalls of the patches; a method to reduce the amount of such polarization conversion is proposed in this article. © 1996 American Institute of Physics. [S0021-8979(96)06008-5]

I. INTRODUCTION

To keep pace with present hard magnetic drives, magneto-optical (MO) recording technology must increase recording density to 10 Gb/in.². Such densities imply recorded domain diameters of the order of 0.25 μm. From a micromagnetic point of view, such domains are stable in the current MO media, which are based on amorphous rare-earth transition metal alloys.¹ The problem is how to write and read back such small domains considering the fact that, even for the blue light, the focused spot at the disk surface is about twice the size of the desired domains. Reading of small marks may be possible with a three-beam scheme² in conjunction with partial response signaling.³ As for writing and erasure, patterning of disk substrates⁴⁻⁵ promises to confine reverse-magnetized domains within areas that are as small as (or even smaller than) the focused laser spot.

Figure 1 presents the main idea behind the confinement of domains on patterned disks. The circle with a radius of 0.4 μm represents the Airy disk for the laser spot with a wavelength of 400 nm, focused through an objective lens with NA = 0.6. The disk substrate is patterned by 0.25×0.25 μm² shallow square patches in the form of a checkerboard. When the laser beam is focused at the center of a patch it nucleates a reverse domain which subsequently expands (under the influence of an externally applied magnetic field) towards the patch borders. The sidewalls of the patch prevent the domain wall from crossing the patch boundary. This confinement is caused by the increased coercivity of the MO film at the sidewalls. The increased coercivity is probably rooted in the tilt of the easy axis of magnetization on the sidewalls, as well as in the reduced film thickness there.⁶ Thus, this technique should allow the writing of magnetic domains smaller than the laser spot. Another advantage of patterned substrates is that the laser beam does not interfere with previously recorded domains since the patch sidewalls prevent the expansion or contraction of existing domains in the neighborhood of the focused spot.

In this article we provide experimental evidence for the strong pinning of domain walls on the sidewalls of shallow patches. Thermomagnetic recording performed on several patterned samples indicates that recorded domains can form within the confines of patches that have a height (or depth) as low as 10 nm. Scanning optical microscopy has been used to identify the source of noise introduced during readout of patterned samples.

II. EXPERIMENT

Corning 7059 glass substrates were patterned using a photolithographic method.⁴ The patterns in the photoresist layer were produced by exposure to optical interference fringes in two orthogonal directions. 2.5×2.5 μm², 1×1 μm², and 0.5×0.5 μm² square patches having height (or depth) of 10, 20, or 30 nm were produced by argon–ion etching through the developed photoresist mask.⁷⁻⁸ The samples used in our study are listed in Table I. The resulting surface features are shown in two typical atomic force micrographs in Fig. 2. If the exposed photoresist is underdeveloped, wells appear in the photoresist film, which, upon ion etching, are replicated into the glass substrate [see Fig. 2(a)]. On the other hand, if the exposed photoresist is overdeveloped, isolated islands remain on the glass substrate [see Fig. 2(b)]. A thin film stack was subsequently deposited on these substrates as follows: substrate/SiN(10 nm)/TbFeCo(either 25 nm or 50 nm)/SiN(80 nm). The MO layer in this stack was an amorphous Tb-rich TbFeCo film having a saturation moment Ms = 190 emu/cm² and a coercivity Hc = 3 kOe at T = 300 K (see Table I).

Figure 3 is a schematic diagram of our custom-built microscope for domain observations, Kerr loop tracing (with a resolution approaching one wavelength of the light), wall motion studies, and scanning optical microscopy. Domain structures were observed in this polarized-light microscope.

![Fig. 1. Schematic diagram showing a checkerboard pattern of 0.25×0.25 μm² square patches on a disk substrate. The 0.8 μm diam circle represents the Airy disk of the focused laser spot, produced with a 0.6 NA objective lens at a wavelength of 400 nm. The small white circle in the middle represents a domain nucleus.](image-url)
TABLE I. Characteristics of the samples used in experiments.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Patch size (µm²)</th>
<th>Patch height (nm)</th>
<th>TbFeCo thickness (nm)</th>
<th>Etched areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.5×2.5</td>
<td>30</td>
<td>50</td>
<td>Low</td>
</tr>
<tr>
<td>B</td>
<td>1×1</td>
<td>20</td>
<td>50</td>
<td>Low</td>
</tr>
<tr>
<td>C</td>
<td>1×1</td>
<td>10</td>
<td>50</td>
<td>Low and high</td>
</tr>
<tr>
<td>D</td>
<td>0.5×0.5</td>
<td>10</td>
<td>25</td>
<td>Low and high</td>
</tr>
</tbody>
</table>

using a 100X oil immersion objective. The observations were recorded with a TV camera and a PC-based frame grabber that allowed image processing for noise reduction. An electromagnet, having a maximum field capability of 9 kOe and a rise time of 50 ms, was mounted under the microscope’s XY stage to provide the necessary fields for domain nucleation and wall motion studies, for thermomagnetic recording, and for loop tracing. The microscope was supplemented with a laser diode operating at λ=780 nm. The laser beam was focused onto the sample by the microscope’s objective lens. The reflected beam was picked up by a differential detection module (polarizing-beam splitter and two photodiodes). The difference and sum signals from the detectors were sampled by an A/D board and were sent to the computer for further processing.

For Kerr loop tracing with submicron resolution, the sampling of detector outputs was synchronized with the sweeping magnetic field. For every value of the magnetic field, the differential and sum signals were sampled and an apparent Kerr rotation angle was calculated. (Faraday rotation in the objective lens was taken into account when the final Kerr angle was determined.) Kerr hysteresis loops obtained with this loop tracer will be discussed later in the article.

To study the peculiarities of domain wall motion with a spatial resolution of better than 50 nm, the magnetic field was brought up to a constant level that allowed a single domain wall to move under the laser spot. The differential output signal was then sampled at equal time intervals (maximum sampling rate=10²/5) and plotted as a function of time. This method allows observation of small Barkhausen jumps during wall motion.¹⁰

For scanning optical microscopy, the polarized-light microscope was equipped with a piezo stage. The piezo stage was computer controlled, its steps being synchronized with the sampling instances of the differential and sum signals from the photodetectors. A two-dimensional plot of the sum signal would represent a reflectivity map of the sample. The corresponding plot of the differential signal would yield a map of the polarization rotation angles occurring at the sample’s surface.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Scanning optical microscopy of patterned samples

Figure 4 shows scanning photomicrographs of patterned samples that were saturated prior to scanning (i.e., there was no magnetic structure within the scanned area). The micrographs were obtained using the differential signal from the detector module. The grey level represents the degree of rotation of polarization. In Figs. 4(a) and 4(b), where the patch size is 2.5×2.5 µm² and the patch height is 30 nm (sample A), black corresponds to a minimum rotation of −3.0° and white corresponds to a maximum rotation of +3.0°. Figure
FIG. 4. Scanning photomicrographs of patterned samples. The samples were saturated in a strong magnetic field prior to scanning. The differential signal picked up during scanning (and used to produce these images) was proportional to the angle of rotation of polarization. The incident polarization was linear along the Y axis. (a) 2.5×2.5 μm² patches having a height of 30 nm. (b) Same sample as in (a) but rotated 45° around the Z axis. (c) 1×1 μm² patches having a height of 10 nm.

4(a) indicates that the patch borders cause a fairly significant rotation of polarization. Specifically, the sidewalls of the patches aligned at ±45° to the direction of incident polarization (which is along the Y axis) produce the strongest rotations. If the orientation of the sidewall relative to the incident polarization is +45° (upper left and lower right corners of each patch) the sidewalls produce negative rotation. For −45° orientation (lower left and upper right corners of each patch) the sense of rotation is positive. The observed rotations are caused by different reflectivities for the p and s components of polarization, where s is perpendicular and p is parallel to the sidewall. If the incident polarization happens to be either parallel or perpendicular to the sidewall, then there would be no rotations at all. The patches in Fig. 4(a) are visible in this differential scanning micrograph essentially because they have rounded corners (at ±45° to the incident polarization). If we rotate the sample by 45°, then

FIG. 5. Domain structure developing under a bias magnetic field in a TbFeCo film on a patterned substrate having 10 nm high, 1×1 μm² patches: (a) at H=2.8 kOe; (b) scanned photomicrograph showing a close-up of a small region in (a); (c) at H=3.4 kOe; (d) at H=4.5 kOe.
the sidewalls themselves become oriented at $\pm 45^\circ$ to the incident polarization, which is the case presented in Fig. 4(b). In Fig. 4(c), where the patches are $1 \times 1 \mu m^2$ and the patch height is only 10 nm (sample C), the minimum rotation angle (black) is $-0.3^\circ$ and the maximum rotation angle (white) is $+0.3^\circ$. The order of magnitude reduction in the polarization rotation angles in the case of Fig. 4(c) as compared to those in Figs. 4(a) and 4(b) indicates that polarization rotation on the sidewalls dramatically decreases with a reduction of the patch height.

B. Magnetic domain structures in patterned samples

Figure 5 shows domain structures developing in the patterned sample C [i.e., the sample with the surface topography of Fig. 2(b)] under a bias magnetic field. At first the magnetic reversal occurs due to nucleation followed by wall motion in the connected areas of the sample, namely in the region between the patches, as shown in the polarized-light micrograph of Fig. 5(a). The scanning optical micrograph of Fig. 5(b) shows how the domain structure bends its way around the patches, leaving behind unreversed islands. In this picture, the advancing domains are black, while the four corners of individual patches appear as two pairs of bright and dark spots. The surviving domains appear as elongated bright spots oriented at $45^\circ$ to the X axis. This apparent elongation of the domain is an illusion caused by the surrounding pairs of bright and dark spots arising from the patch corners: the dark spots compress the domain image in one direction, while the bright spots stretch it in the perpendicular direction. At a certain magnetic field the entire region in-between the patches becomes saturated, while within the patches magnetization remains unreversed [see Fig. 5(c)]. Apparently, the patch sidewalls prevent domain walls from entering the patches. At higher magnetic fields the domains confined within the patches begin to collapse either by domain wall penetration through the sidewalls or by nucleation of reverse domains from within the patches [see Fig. 5(d)].

Figure 6 shows a micro-Kerr loop, measured in sample C, using a $2 \mu m$ diam probe laser beam ($1/e$ intensity radius $=1 \mu m$). The beam covers a region that contains only a few patches (a minimum of one and a maximum of four), thus allowing us to obtain information about individual patch reversals. The sharp drop in the Kerr signal in the vicinity of 2.8 kOe corresponds to magnetization reversal in the connected regions between the patches. The three jumps that follow the first one at magnetic fields between 2.8 and 4.8 kOe correspond to individual reversals within the three patches that are apparently illuminated by the focused beam in this experiment. The different heights of the jumps are due to uneven illumination of the patches.

The domain structure under a bias magnetic field in sample D, which has $0.5 \times 0.5 \mu m^2$ patches, is shown in Fig. 7(a). Since optical microscopy fails to resolve domain features on such a small scale, we employed an atomic force microscopy (AFM) and a magnetic force microscope (MFM) for these observations. In Fig. 7(a) the MFM picture shows domains expanding in the connected areas between the patches. [The AFM picture of Fig. 7(b) shows the same region of the sample where the patches are white and the space between them is black.] In a good portion of the MFM picture, the black domain structure has developed in the connected areas of the sample, but it has not penetrated through the patch borders.

Figure 8 shows a micro-Kerr loop, measured for sample D, using a $2 \mu m$ diam probe beam. The first jump of the Kerr signal in the vicinity of $H=2.6$ kOe corresponds to fast domain expansion in the connected areas between the patches.
The next five jumps between $H = 2.6$ and $H = 3.6$ kOe correspond to individual patch reversals. As before, different magnitudes of the jumps are caused by uneven illumination of the patches within the focused beam.

These observations of magnetization reversal on patterned substrates indicate that the patch sidewalls prevent domain walls from entering the patches. At room temperature the strength of this sidewall pinning varies from a maximum of 1 kOe in the 0.5×0.5 μm$^2$ patches to a maximum of 2 kOe in the 1×1 μm$^2$ patches (both patches having a height of 10 nm). This difference may be due to the better quality of the 1×1 μm$^2$ patches fabricated with our photolithographic process. One conclusion that we may draw from this study is that pinning on the sidewalls should also occur when a domain nucleates inside a patch and proceeds to expand towards the sidewalls. It must therefore be possible to confine such domains within the patch borders.

C. Thermomagnetic recording and erasure experiments on patterned samples

Figure 9 shows results of thermomagnetic recording and erasure on patterned samples. The 780 nm laser beam was directed through a 1.25 NA immersion oil objective onto individual patches and, with the aid of an externally applied magnetic field, effected the writing and/or erasing of domains. The domains in Fig. 9(a) were written inside the patches of the initially saturated sample B under a reverse field of 1.3 kOe using a 10 mW, 200 ns laser pulse. Good confinement of domains within individual patches is observed. In Fig. 9(b), the application of 10 mW, 200 ns laser pulses has produced erasure of selected domains on sample C, which was described earlier in conjunction with Fig. 5; the pattern of domains before erasure of selected patches may be seen in Fig. 5(c).

Figure 10(a) shows domains written on 1×1 μm$^2$, 20 nm high patches (sample B) under a reverse field of 1.3 kOe, using 10 mW, 200 ns laser pulses. Compare this with Fig. 10(b), where...
appearing in the differential channel output are caused by polarization rotation at patch corners, as discussed earlier. To prevent the signal of the patches from appearing alongside the MO signal in the differential channel output, one must fabricate perfectly square patches whose sides are aligned strictly parallel and perpendicular to the direction of polarization of the incident beam.

IV. CONCLUSIONS

Kerr loop tracing on micrometer-sized regions and scanning optical microscopy with polarization detection have been employed to study magnetization reversal on patterned substrates. Pinning of domain walls in TbFeCo films by the sidewalls of shallow patches on patterned glass substrates has been demonstrated. Also, thermomagnetically written domains have been shown to be successfully confined within the patches. The angle of rotation of polarization, caused by different reflectivities of the patch corners for \(p\)- and \(s\)-polarized light was measured, and a method to eliminate this undesirable signal was proposed.

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