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DOMAIN WALL PINNING IN AMORPHOUS TbFeCo FILMS ON PATTERNED SUBSTRATES (Invited)

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Abstract - Magnetization reversal in amorphous TbFeCo films on patterned glass substrates was studied. Two types of patterns were examined: grooves and square patches. Pinning of the domain walls at the side-walls of the patterns was observed. The pinning depends on the depth of the patterns and the angle of the side-walls: greater depth and steeper side-wall produce stronger pinning. Thermomagnetic recording experiments confirm the ability of patterned substrates to confine recorded domains within boundaries defined by the side-walls.
KEY WORDS: Patterned Substrate, Magnetic Domain Confinement, Domain Structure, Thermomagnetic Recording

1. Introduction

For future generations of magneto-optical (MO) drives the recording density goal is 10 Gb/sq.in, which implies domain diameters of the order of 0.25 μm. Such domains have been shown to be stable in RE-TM films under certain conditions [1-2]. These conditions imply substantial motion of the domain wall which, in media such as amorphous RE-TM films, can lead to uncertainties in the final domain diameter by as much as a tenth of a micron [3]. Another problem is that, even for blue light recording, the laser spot at the disk surface is about twice the size of the final domain, which implies that the beam can interfere with previously recorded domains while writing new domains and, therefore, lead to partial or total erasure of these domains.

One way to handle these problems is the patterning of the disk substrates. Patterning in the form of shallow radial grooves, for example, can give rise to a periodic variation of coercivity (H_c) along the tracks [4]. This profile of coercivity may originate from a number of different factors: tilt of the easy axis of magnetization on the side-walls of the (radial) grooves, change of film thickness on the side-walls compared to that on land and groove regions, increased roughness of the side-walls induced by the fabrication process, and difference in coercivity between grooves and lands due to differences in surface roughness [4-5]. Recording on a patterned disk may begin by nucleation of a tiny domain in the central region of a focused laser beam, followed by the expansion of this domain under an external magnetic field. Under these conditions, the coercivity profile will pin the domain wall in predefined positions, thus confining the written domain within a desired area on the patterned substrate. Other advantages of substrate patterning may be the reduction of jitter and a better synchronization while writing and reading data using a clock signal that is generated from the periodic pattern itself.

In the present paper we study the magnetic properties of TbFeCo films sputtered on patterned glass substrates, and, in particular, show the pinning of the domain walls by the side-walls of the patterns. Thermomagnetic recording has been performed on the patterned samples, confirming the ability of the underlying structures to confine the written domains.

2. Experimental

Sample preparation

Patterned glass substrates were fabricated using a photolithographic method. The patterns in the photoresist were produced by exposure to an optical interference pattern or, alternatively, by exposure through a striped mask, followed by resist development. Three different types of glass have been used: soda lime, fused silica, and Corning 7059. The patterns on these glass surfaces were etched by argon-ion or freon-ion milling. Figure 1(a) shows a typical Atomic Force Microscope picture of a grooved surface after ion milling. If two striped optical patterns are allowed to overlap at 90° on the photoresist, then, after ion etching, we obtain square patches of unetched glass surrounded by valleys of milled glass, as can be seen in the electron micrograph shown in Fig.1(b).

The grooves studied in this work had a period of 1 μm (with 50% duty cycle) and a depth varying from 3 nm to 400 nm. We also studied two sets of samples with square patches, one set having 2.5x2.5 μm^2 squares, the other having 24 x 24 μm^2 squares, with heights varying from 10 nm to 40 nm in each case. The angle of the side-walls of the grooves/patches relative to the surface normal was nearly 45° for argon-etched samples and 20° for freon-etched samples. The thin film structure deposited on the patterned substrate was as follows: glass / SiN(10 nm)/ TbFeCo(50nm) /SiN (80 nm). The SiN layers protected the magnetic film against oxidation. The MO layer itself was an amorphous Tb-rich TbFeCo film having a saturation moment M_s=190 emu/cm^3 and a coercivity H_c= 3 kOe at T=300 K.

The magnetic properties of amorphous RE-TM and other MO films depend strongly on the quality of the substrate [6-7]. Ion milling of the glass substrates used in our experiments could cause significant modifications of the surface [8]. The most important of these changes were related to roughness and the effective chemical composition. The final roughness and composition depended not only on the initial roughness, but also on the chemical purity of the glass. Due to high selectivity, freon etching produces rough surfaces on those glasses that contain impurities. In contrast, the etching rate for argon ions is almost independent of the type of impurities. (Rough surfaces become smooth after argon milling). If the initial surface is perfectly smooth and without impurities, then both argon and freon milling have the same effect on the quality of the surface, replicating the initial smoothness into the final surface. Corning 7059 glass shows such independence from the nature of the etching gas, while the properties of soda lime and fused silica surfaces can be significantly modified by the milling process. This has been confirmed by the measurement of roughness on freon- and argon-etched substrates. In the case of freon-ion etching, starting with an initial r.m.s. roughness of 5 Å, the final roughness of soda lime samples was ~ 40 Å and that of fused silica samples was ~ 10 Å, whereas the Corning samples maintained their original roughness. The increased roughness produced several kilo Oersted increase of coercivity for the MO films on soda lime, and several hundred Oersted increase for films on fused silica. Freon-etching didnot change the coercivity of our samples on Corning 7059 substrates. In the case of argon-ion milling the r.m.s. roughness decreased from 5 Å to about 3 Å for all types of glasses, producing about one kilo Oersted decrease of the coercivity of the TbFeCo films grown on etched soda lime substrate, and several hundred Oersted decrease for films on fused silica. The coercivity of TbFeCo films on argon-etched Corning 7059 substrate was very close to that of the films on unetched Corning glass.

Measurement techniques

The profiles of grooves and patches and the roughness of the substrates were measured using atomic force and scanning electron microscopy. The magnetic properties of the samples were studied using vibrating sample magnetometry in fields up to 14 kOe. The magneto-optic and Hall loops, and the initial magnetization curves were obtained in a loop tracer in fields up to 20 kOe [9]. Domain structures were observed in a polarized-light microscope using high-NA objectives and, in certain situations, a 100x oil immersion lens (see Fig.2(a)). The observations were recorded with a TV camera and a PC-based frame grabber that allowed image processing for noise reduction [10]. A single-pole, conical-tip electromagnet, having a maximum field capability of 5 kOe, was mounted under the microscope's XY stage to provide the necessary fields for domain growth and contraction, as well as a bias field for thermomagnetic recording. The microscope was equipped with a semiconductor laser diode for domain writing and

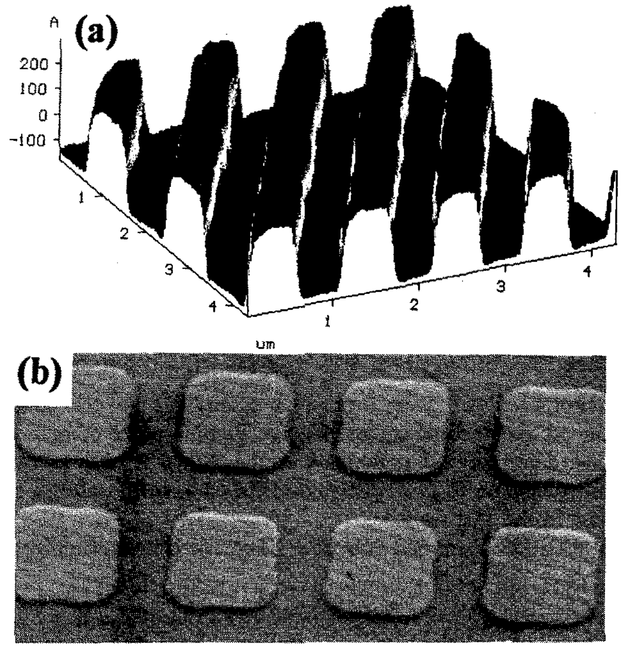

Fig.1.(a) AFM picture of grooves etched by argon ions on soda lime glass. (b) 2.5x2.5 μm^2 patches on a Corning 7059 glass substrate obtained by exposure of the photoresist through masks, followed by resist development and freon milling.

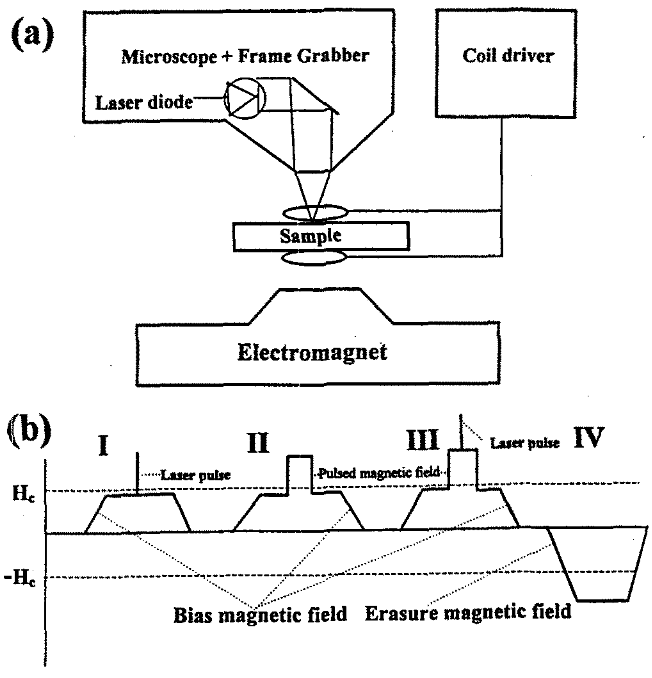

Fig.2. (a) Experimental setup for observations of domain recording and domain wall propagation. (b) Pulse sequences for recording, expansion, and erasure of magnetic domains.

erasure experiments.

A pulsed magnetic field was also produced by two coils attached to the opposite surfaces of the sample. Pulsed current with an amplitude of up to 20 A was supplied by the coil driver. The coils could produce a magnetic field of 150 Oe/A, with rise and fall times of about 300 ns; the duration of the pulses could vary from 600 ns up to several

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milliseconds. Figure 2(b) shows several possible combinations and relative timing of the bias magnetic field, the pulsed magnetic field, and the laser pulse. Case I shows the sequence of bias magnetic field and the laser pulse used for writing a domain. Case II provides for the expansion of a recorded domain using a magnetic field pulse. Case III corresponds to recording a domain with a laser pulse and simultaneously expanding it with a magnetic pulse. Case IV represents the erasing of existing domains in preparation for the repeat of the recording and expansion experiments.

3. Results and discussion

Pinning of domain walls due to coercivity differences on lands and grooves

Since argon-ion etching smoothes the surfaces of soda lime and fused silica glasses, the magnetic properties of TbFeCo films deposited on the etched grooves differ from those on the unetched lands. Figure 3(a) shows the domain structures developing in a TbFeCo film deposited onto a grooved fused silica substrate milled by argon ions. The left half of the picture represents a region with etched grooves and unetched lands, whereas in the right half both lands and grooves have been subjected to repeat etching after removal of the residual photoresist. In the left half of the sample the lower coercivity of the etched grooves allows their complete magnetic reversal before the unetched lands begin to reverse. This behavior manifests itself in a kink on the magneto-optical loop from the left half of the sample, shown in Fig. 3(b). The small shift of the kink from the midpoint of the loop indicates that the grooves are wider than the lands on this particular sample. The right half of the sample in Fig. 3(a) shows simultaneous reversals on lands and grooves; no kink is observed on the MO loop measured in this region (see Fig.3(c)). The coecivity in the right half of the sample is close to that observed within the etched grooves on the left half. Although in the right half of the sample the coercivities of grooves and lands are equal to each other, preferential motion of domain walls along the grooves is still observed, indicating a certain amount of pinning of the domain walls by the side-walls.

When the coercivities of grooves and lands are different, it is difficult to distinguish whether the pinning of the domain wall at a side-wall is due to the side-wall itself, or caused by the difference between the coercivities of grooves and lands. In this case better results can be obtained using a pulsed magnetic field for domain expansion. Figure 4(a) shows the domain structure in a TbFeCo film deposited onto a grooved soda lime substrate milled by argon ions. The grooves have a period of 1 μm and a depth of 20 nm. The domains have been obtained after the consecutive application of pulse sequences I and II of Fig. 2(b). The central white spot in the middle of the long domains is the initial domain written by the laser pulse. The picture clearly indicates that the domain walls can move along the grooves

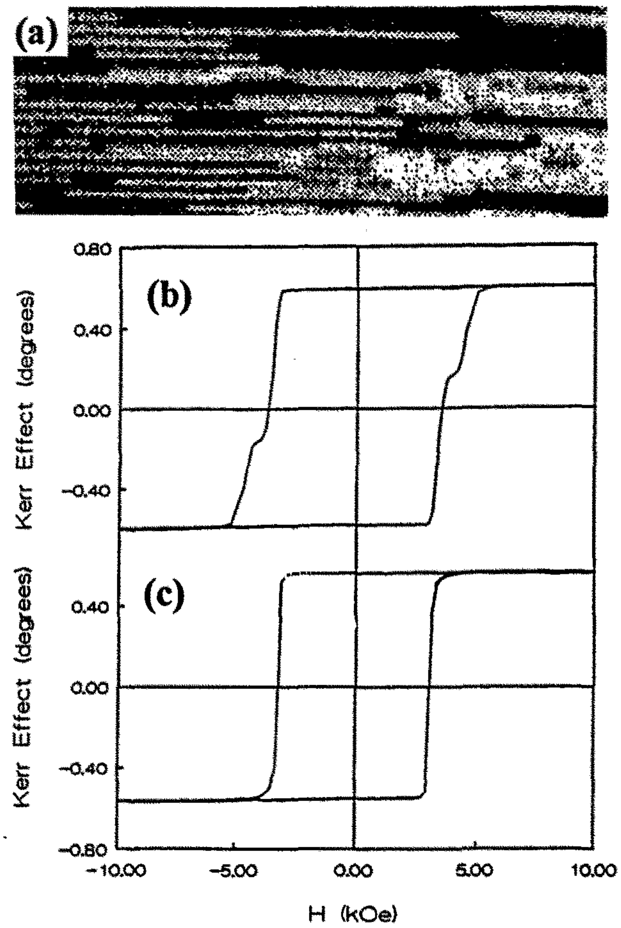

Fig. 3. (a) Domain structure developing in a TbFeCo film on grooved fused silica substrate. The groove depth is 40 nm, and its period is 1 μm. The left side contains etched grooves and unetched lands. In the right side both grooves and lands are etched. (b), (c) Kerr loops measured in the left and right regions, respectively.

but cannot cross the side-walls, even when the pulsed field is as strong as 1.6 kOe. (The difference between the coercivities of land and groove for this sample was about 800 Oe.) This puts a lower limit of 1.6 kOe on the pinning force of the side-walls.

In very shallow grooves domain walls can move across the side-walls [4]. Using a pulsed magnetic field, it is possible to measure the difference of domain wall velocities along and across the grooves. Figure 4(b) shows the domain structure developing on 3 nm deep grooves, obtained after the consecutive application of sequences I and II of Fig. 2(b). Again, the central white spot is the initial domain written by the laser pulse. The picture indicates that the velocity of the domain wall along the grooves is about 10 times greater than that in the direction perpendicular to the grooves. This anisotropy of wall motion velocity is most probably rooted in the pinning by the side-walls, but it may also be caused by the different dynamic coercivities of grooves and lands.

TbFeCo films on grooved fused silica or soda lime substrates milled by freon show a very different magnetization reversal behavior. The reversal in this case begins on the unetched land, indicating that freon milling of the grooves has introduced additional roughness and, therefore, increased the coercivity.

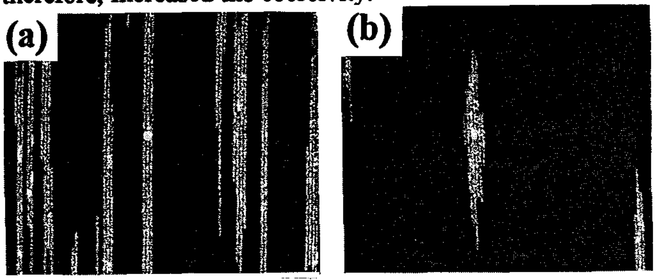

Fig. 4. Domain structures in TbFeCo films on soda lime substrate containing 1 μm period grooves milled by argon ions. The pictures were taken after the application of pulse sequences I and II of Fig. 2(b). The central white spot in each picture is the initial domain written by the laser pulse. (a) Groove depth = 20 nm, bias magnetic field H_b = 2.4 kOe, pulsed magnetic field H_p= 1.6 kOe with a duration of 11 μs. (b) Groove depth = 3 nm, bias magnetic field H_b = 2.17 kOe, pulsed magnetic field H_p = 1.6 kOe with a duration of 10 μs.

Magnetic properties of deep side-walls

To examine the properties of the side-walls in more detail, Hall loops were measured for a 400 nm deep grooved sample etched by freon on fused silica substrate. Since the surface area of the side-walls was large, the Hall signal from them was comparable in magnitude to the signal from grooves and lands. The magnetic field was applied at different angles Ψ_H relative to the surface normal as shown in Fig. 5. In the figure the arrows on the surface represent the electric current I, while the arrows in the cross-section show the magnetic moments M. Since the extraordinary Hall effect signal is proportional to the component of magnetization perpendicular to the direction of current flow, and since the current flow is along the film surface, the equivalent flattened geometry at the bottom of Fig. 5 applies.

Figure 6(a) shows the Hall loop obtained at $\Psi_H = 0°$. The sharp drop in the Hall signal between 3 kOe and 4 kOe corresponds to magnetization reversal within grooves and lands. Between 5 kOe and 15 kOe the domain walls sweep through the side-walls. Since the effective widths of grooves, lands and side-walls are approximately equal, one may infer from this loop that the magnetization is perpendicular (or nearly so) to the film surface everywhere, including on the side-walls.

Figure 6(b) shows the Hall loop obtained at $\Psi_H = 70°$, where the magnetic field is perpendicular to the left side-wall. The sharp drop around H = 4.5 kOe now represents reversal within the grooves and lands. The more gradual change of the signal around H=7 kOe indicates reversal on the left side-wall. The section of the curve with a positive slope around H = 9 kOe represents magnetization reversal on the right side-wall. The total signal from the side-wall reversal in this case is smaller than that in Fig. 6(a), indicating that some of the reversals on opposite side-walls

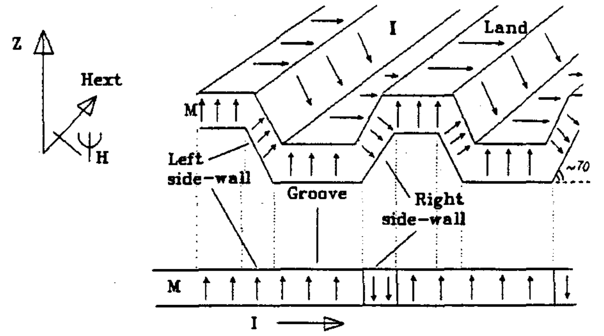

Fig. 5. Distribution of magnetization **M** and electric current **I** in a MO film coated on a grooved substrate. The flattened view from the edge shown in the lower part of the figure emphasizes the fact that the magnetization of the right side-wall has been reversed.

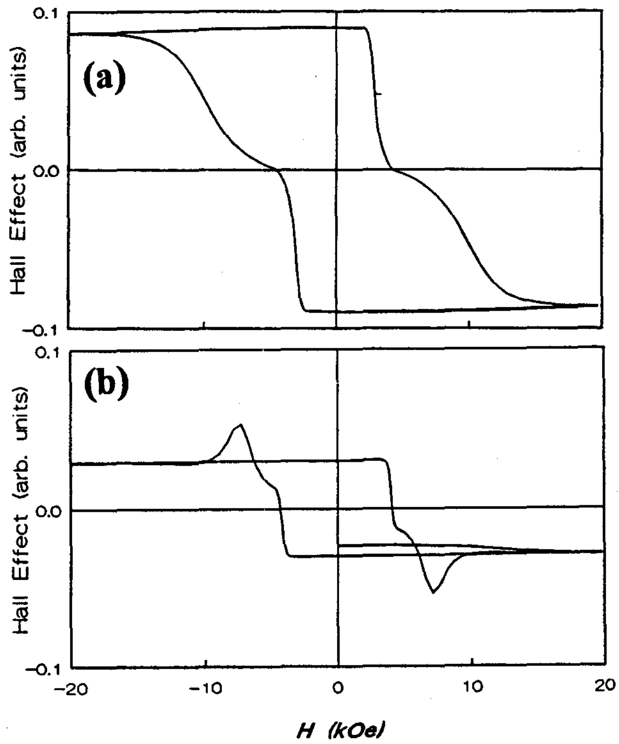

Fig. 6. Hall loops for a TbFeCo film on a grooved substrate with 1 μm period and 400 nm deep grooves. (a) The magnetic field is applied normal to the plane of the sample. (b) The magnetic field is applied at Ψ_H =70° to the normal.

occur at the same time, causing partial cancellation of their Hall signals. Also, the smaller signal from lands and grooves compared to that in Fig.6(a) implies incomplete reversal in these regions due to the obliquity of the applied magnetic field.

Pinning of domain wall by the side-wall

Argon or freon etching does not seem to affect the surface roughness of the Corning 7059 glass. The coercivities of TbFeCo films on etched and unetched Corning substrates were almost the same. To measure the strength of the pinning caused by the side-walls, square patches were

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etched on the surface of this substrate (see Fig. 1(b)). Figure 7 shows the domain structure developing in a TbFeCo film on a Corning substrate that has 24 x 24 μm^2 patches with a height of 40 nm. The domains are confined to a certain degree within the patches, thus indicating the effectiveness of pinning by the side-walls. Simultaneous development of domains in the areas in between the square patches indicates that the coercivities of the etched and unetched regions are nearly identical.

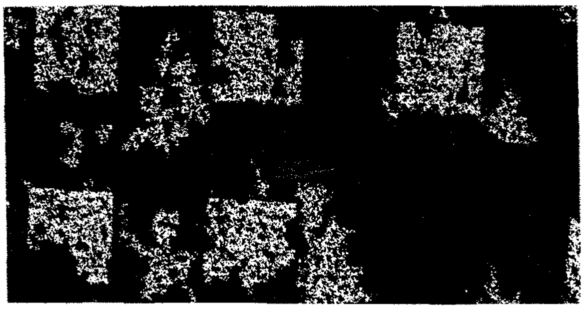

Fig. 7. Domain structure developing in TbFeCo film on a Corning glass substrate. The patterned substrate milled by argon contains 24x24 μm^2 square patches with a height of 40 nm. The sample was initially saturated in a field of 5 kOe, and then subjected to a reverse field of 2.9 kOe.

The strength of the pinning by the patch side-walls was estimated using pulsed magnetic fields. A domain was initially written within a patch by a laser pulse, and then expanded to the patch borders using the bias magnetic field. The expanded domain is shown in Fig. 8(a), where the square domain at the center appears to be well confined, except for the upper-right corner, where a defect of the side-wall seems to exist. After application of a bias plus pulsed magnetic field (case II, Fig. 2(b)) with a total magnitude exceeding the coercivity of the sample by 1.1 kOe, the domain wall crosses the side-walls along the entire perimeter of the patch, as shown in Fig.8(b). If the amplitude of the pulsed magnetic field is below 600 Oe, the domain cannot cross the side-walls (see Figs. 6(c) and 6(d)) except in one place near the lower-left corner of the patch where a defect of the side-wall may exist. (The domains near the upper corners of the patch existed before the application of the magnetic field, and only developed further after the pulse was applied.) This study indicates that the strength of the domain wall pinning at 45° side-walls having a height of 40 nm is about 600 Oe. A similar experiment was performed on a TbFeCo film on the Corning substrate containing 40 nm high, 2.5 x 2.5 μm^2 patches. The pattern was produced by freon milling, which tends to produce steeper side-walls. The strength of the pinning observed in this case was nearly 1.6 kOe.

<u>Thermomagnetic recording on patterned samples</u>

In the preceding sections we showed that the side-walls of

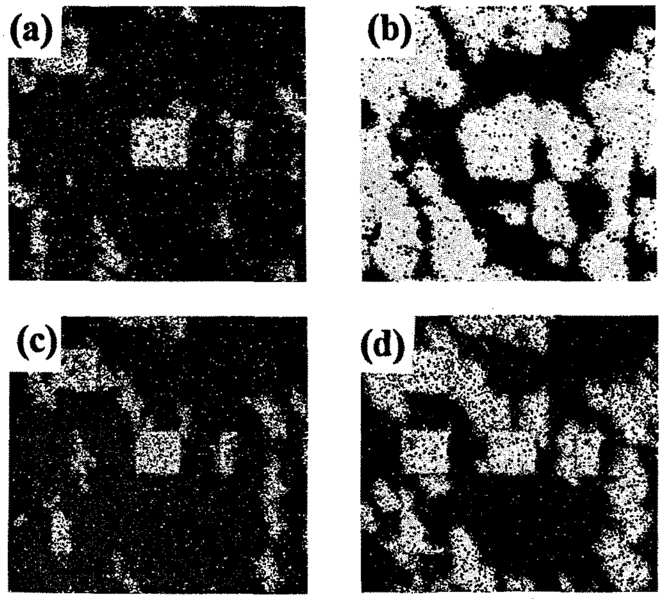

Fig. 8. Domain structures in a TbFeCo film on Corning substrate, patterned by argon-ion milling. The pattern consists of 40 nm high 24x24 μm^2 patches. (a) After the application of pulse sequence I to the central patch of the sample, followed by expansion of the recorded domain under a 2.9 kOe bias magnetic field. (b) Domain structure developed by the pulse sequence II from the initial state of Fig. 8(a) . The bias field is H_b = 2.78 kOe, and the pulsed field is Hp=1.1 kOe. (c) Domain structure obtained under the same conditions as in Fig. 8(a), in the same region of the sample, after erasing the previous domain pattern in a 5 kOe field. (d) Domain structure developed by the pulse sequence II from the initial state of Fig. 8(c). The bias field is H_b = 2.78 kOe, and the pulsed field is Hp= 0.6 kOe.

grooves and patches can pin the domain walls of TbFeCo films at the room temperature. For thermomagnetic recording the pinning should occur at elevated temperatures during the writing process. Figure 9(a) shows domains written on a patterned sample containing 2.5 x 2.5 μm^2 square patches using the pulse sequence III of Fig.2(b). The laser power was delivered in a 15 mW, 2 μs pulse, the bias magnetic field was H_b =2.34 kOe, and the pulsed field was H_p = 1 kOe. For comparison, Fig. 9(b) shows domains written on the same patches but without an external magnetic field. The domains are now smaller because their walls were not forced to move towards the patch boundaries during the recording process. Figure 9(c) shows domains written under the same conditions as those in Fig. 9(a), but on an area of the sample that did not contain patches. The domains written in this flat area are not only larger than those in the patterned region, but also their magnetization is broken up into a maze-like pattern.

Figure 10 presents the results of an experiment in which domains that had been written in a process similar to that described in conjunction with Fig. 9(a), were erased thermomagnetically. Initially, domains were written to form the pattern shown in Fig. 10(a). Then sequence III of Fig. 2(b) with negative sign for the magnetic fields was applied

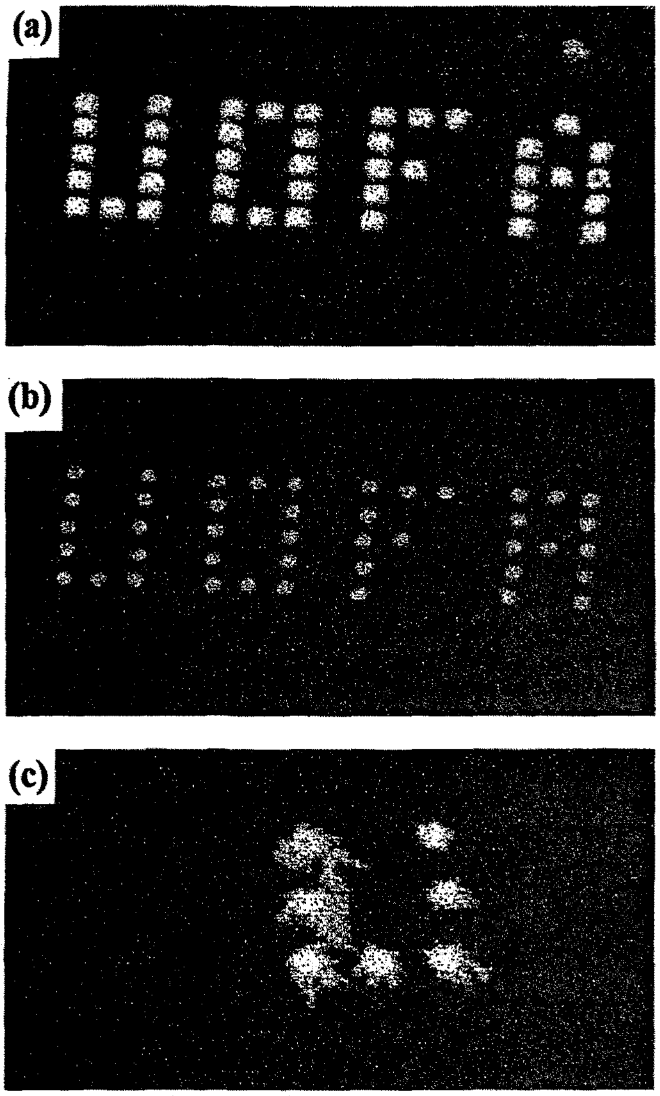

Fig. 9. (a) Domains written in a TbFeCo film on a Corning glass substrate. The pattern, etched by freon ions, consisted of 2.5x2.5 μm^2 square patches with a height of 20 nm. The domains were written using sequence III of Fig. 2(b). (b) Same as (a) but with no magnetic fields applied during thermomagnetic recording. (c) Domains written in the TbFeCo film on a flat region of the Corning substrate. The conditions of recording were identical to those used in (a).

to every other recorded patch. The result is shown in Fig. 10(b). The reduced contrast of the remaining domains indicates that partial erasure has occurred in their central regions. We expect for smaller patches (less than 1x1 μm^2) that much lower laser power levels will be needed to create a temperature profile that would allow recorded domains to expand to (or shrink from) the borders of the patches. Under these conditions, partial erasure of neighboring domains should not occur.

4. Conclusions

Pinning of the domain walls in TbFeCo thin films on patterned glass substrates has been observed. The pinning at the side-walls of grooves and patches originates either from the differences in the coercivities of grooves and lands, or from the pinning by the side-walls themselves. The coercivity differences arise from the etching of substrates that have impurities and rough surfaces (e.g., soda lime and fused silica glasses). The coercivity of the side-walls depend on their slopes and widths. A 40 nm-high patch with a side-wall slope of 45° gave rise to a pinning coercivity of about 0.6 kOe, while for a 20° slope and the same height the pinning strength was nearly 1.5 kOe. Hall effect measurements performed on a deep grooved sample (400 nm) showed that the anisotropy axis is perpendicular to the side-walls, and that the coercivity of the side-wall is greater than that of grooves and lands. Confinement of thermomagnetically written domains within square patches formed on a glass substrate was also demonstrated.

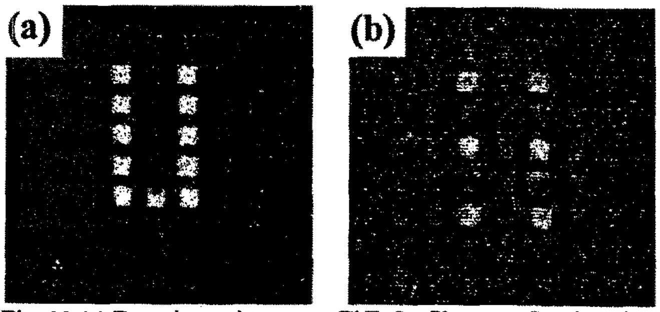

Fig. 10 (a) Domains written on a TbFeCo film on a Corning glass substrate. The pattern consisted of 2.5x2.5 μm^2 square patches with a height of 20 nm. Sequence III of Fig.2(b) was used in recording the domains. The 15 mW laser pulse was 2 μs long, the bias magnetic field was H_b = 1.88 kOe, and the 30 μs pulsed magnetic field was H_p= 1.4 kOe. (b) Erasure of every other domain with the same pulse sequence but with the polarity of the magnetic fields reversed.

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REFERENCES

1. H. Fu, R. Giles, M. Mansuripur, G. Patterson, Computers in Physics 6, 610 (1992).
2. D. Rugar, C.-J. Lin, R. Geiss, IEEE Trans. Magn. 23, 2263 (1987).
3. H.P.-D. Shieh, M.H. Kryder, J.Appl. Phys. 61, 1108 (1987).
4. S. Gadetsky, T. Suzuki, J.K. Erwin, M. Mansuripur, Proc. of MMM-InterMag'94 Conference, paper BC-08.
5. Y.-C. Hsieh and M. Mansuripur, "Coercivity of magnetic domain wall motion near the edge of a terrace", submitted to J. Appl. Phys.
6. J. Calkins, M. Mansuripur, M. Ruane, Mater. Rec. Soc. Symp. Proc. 80, 435 (1987).
7. C.-H. Chang, M.H. Kryder, J.Appl. Phys. 75, 6864 (1994).
8. O. Auciello, R.Kelly, Ion Bombardment Modification of Surfaces, ELSEVIER (1984).
9. R.A. Hajjar, T. Wu, M. Mansuripur, J. Appl. Phys. 71, 813 (1992).
10. B.E. Bernacki, M. Mansuripur, J. Appl. Phys. 69, 4960 (1991).