Recorded mark observation by spin-polarized scanning electron microscopy

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Abstract

We observed the shape and size of marks recorded magneto-optically on TbFeCo film, using spin-polarized scanning electron microscopy (spin SEM). We studied the laser power dependency of the marks recorded on a land/groove substrate. When larger power was used, the land/groove border acted as a barrier to the propagation of the magnetization reversal, which confirmed the advantage of using a land/groove substrate for high-density recording. We also looked at the film roughness dependency of the marks. We found that the magnetization reversal processes depend on the underlayer roughness, which is related to the irregularity of the mark shapes and the recording noise.

1. INTRODUCTION

The recorded mark shapes and sizes in magneto-optical recording media are of considerable importance in data storage. The success of magneto-optical recording depends on the reliable and repeatable reversal of magnetization in a micron-sized area. To achieve higher density in magneto-optical recording, smaller uniform marks should be recorded precisely in narrow tracks to avoid mark shape irregularity, which decreases C/N ratio, and the cross write, in which the marks extend into the adjacent tracks.

To study the shapes and sizes of the recorded marks, domain observation in high resolution is required. Spin-polarized scanning electron microscopy (spin SEM) is a useful method for studying magnetic domains. In spin SEM, the sample surface is scanned point by point with a focused beam of high-energy electrons. Polarized secondary electrons emitted from the sample surface, which retain the spin-polarization orientation characteristics of the local region of the sample, are spin-analyzed. The authors recently achieved a spatial resolution of 20 nm and we also made it possible to detect all three magnetization components including the one perpendicular to the sample surface by using a specially designed spin rotator. Spin SEM can also detect magnetization information independent of sample surface topography. Thus, it is useful for investigating samples with uneven topographies such as a magneto-optical medium on a grooved substrate, or an underlayer with surface roughness.

Using spin SEM, we studied two aspects of the recorded mark shapes of the magneto-optical medium TbFeCo. In the first study we determined the laser power dependence of mark shapes and sizes in a land/groove recording. This work is an elaboration of an earlier letter, and is for improving high density recordings. Because the track pitch becomes small in land/groove recording, the cross write is thought to be a serious problem, as well as cross talk and cross erase.

Several observations of magnetized domains on grooved substrates have been reported and a phenomenon has been observed in which the written marks on the grooved substrate do not expand across the borders between lands and grooves. Kesteren et al. observed the phenomenon for marks on CoPt film prepared on a V-grooved substrate using magnetic force microscopy (MFM). However, CoPt, which is studied as the magneto-optical medium of the next generation, has different characteristics from the TbFeCo currently used as a magneto-optical medium. Gadetsky et al. observed this phenomenon of TbFeCo film in the field-induced magnetization reversal process on the grooved substrates and in thermomagnetically recording on the patched substrate by using a polarized-light microscope. To investigate the cross-writing effect of land/groove recording more detail, we need to observe marks recorded under actual condition. In this study we observed marks recorded thermomagnetically on both lands and grooves of TbFeCo film.

Our second study describes the relation between the mark shapes for TbFeCo recording film and its underlayer-roughness, which were prepared on V-shaped grooves. In a previous paper, we reported that the shapes of the recorded marks tend to be uniform on the rough underlayer though they are more irregular on the smooth underlayer, which are closely related with the noise characteristics. In this study, we investigated the role of the underlayer-roughness in forming the mark shapes. We observed the applied field dependencies of the mark shapes on TbFeCo films on both the smooth and the rough underlayers. The relation between the recording characteristics and the magnetization reversal process of these two media is discussed.

2. EXPERIMENT
3. RESULTS AND DISCUSSION

3.1 The marks on the land/groove substrate

Figure 2 shows domain images of recorded marks of TbFeCo on lands (a) and grooves (b), and it also shows a higher magnification image of marks on grooves recorded using low laser power (c). The contrast is dependent on the magnetization component perpendicular to the surface of the sample. In this figure the laser beam runs from left to right.

In Figs. 2 (a) and 2 (b), various lengths of recorded marks as used in the mark-edge recording are observed. Because of the multi-pulse recording as shown in Fig. 1[14], the widths of the marks are almost the same in each track and independent of the mark lengths. The shapes are almost the same for lands and grooves and sizes are slightly larger on lands than on grooves. This suggests that coercivity is larger on grooves than on lands. At a laser power of 2.7 mW tiny marks with distorted shapes were observed on grooves (Fig. 2 (c)), while oval-shaped marks were recorded on lands. This means 2.7 mW is not sufficient to form uniform domains against the coercivity on the grooves. As the recording laser power increases the mark sizes become large. In the region of high laser power, even a preheating laser created tail-like irregularities. In addition, the side edges of marks are flat at the borders between lands and grooves, which is more obvious in the marks on grooves.

Figure 3 shows the laser power dependencies of average sizes of marks (some of which are not shown in Fig. 2), with shortest nominal length. The mark sizes, except for the mark width on grooves, increase with the laser power as previously reported.[16,17] In thermomagnetical recording, the area of the magnetization reversal depends on the temperature distribution created by the laser, higher laser powers can create larger marks. On grooves mark width seems to saturate with a value of 0.7 µm around 5 mW while mark length continuously increases. In this region, the widths of marks already reach the width of the track and side edges of marks flatten along the border lines as Fig. 2 (b) shows. This means that marks do not extend into adjacent tracks and mark width saturates even when laser power is high enough. The effect is not very clear in marks on lands, where mark sizes increase monotonously both in width and length as laser power increases. This is because the land width 0.8 µm is wider than that of grooves, and laser power is not sufficient to saturate mark width. However, as Fig. 2 (a) shows, the upper edges of the sides of marks have already reached the borders of grooves and flattened in the region of the high laser power, where marks were not recorded at the exact centers of tracks. Mark width is limited by track width and marks cannot expand to adjacent tracks.

Borders between lands and grooves seem to prevent recorded marks from expanding to adjacent tracks. In other
words, the borders stop the magnetization reversal process, which was reported by Gadetsky et al.\[11\]. There are several possible factors for this phenomenon. Gadetsky et al. suggested that one of those factors may be the difference in the coercivities of grooves and lands. Larger coercivity on either lands or grooves stops the wall motion on the other with smaller coercivity. In our experiment, however, this prevention is also occurred to the mark expansion from the grooves where the coercivities are larger, to the lands where the coercivities are smaller. Therefore the difference of the coercivities is not crucial element in our experiment.

Gadetsky et al. suggested another factor: that the borders themselves have the pinning effect. The simulation\[18, 19\] shows the presence of spatial variation in the magnetic parameters of the material, such as
anisotropy energy, affects the pinning force. In Fig. 2, the color at the borders is gray, which means the perpendicular magnetization component at the border is smaller than that on the other areas of the lands and grooves. This agrees with a previous work[11] which confirmed that the anisotropy axis at the borders directs to the different direction from those at other areas due to the difference of the surface inclination angles. Therefore the magnetic characteristics are different such as in the anisotropy between the borders and the other areas, and the prevention of the wall motion may be caused by the pinning effect related with the magnetic characteristics at the borders.

The thermal conductivity at the borders must also be considered since we recorded the marks thermomagnetically. The film thickness at the borders must have a tendency to be thinner than that on the other areas in the sputtering because of the surface inclination. This causes a decrease in the thermal conductivity and the mark expansion might be prevented in the thermomagnetic recording at the borders. As described above, there are several possible causes why the wall motion is stopped and further experiments are needed to explain the mechanism of the pinning.

This stopping of the wall motion is useful because we can keep recorded marks within tracks even if the laser power exceeds the proper value to some extent. This means that borders increase the laser power margin for recording. We can say that cross write, which has been considered to be a serious problem in land/groove recording, rarely happens in this kind of magneto-optical medium.

3.2 The marks on the rough and smooth underlayer

Previously we studied the underlayer roughness dependence of the noise characteristics[13]. By smoothing the underlayer surface the noise of the non-recorded state can be decreased, whereas the noise level of the recorded state does not change so much. This means the recording noise, which is defined by subtracting the noise of the non-recorded state from that of the recorded state, is increased by smoothing the underlayer surface. This is explained by the difference in the mark shapes recorded on both smooth and rough underlayers, as shown in Figs. 4(a) and 4(b) respectively. The mark shapes on the smooth underlayer are irregular, but, those on the rough underlayer are more uniform. This can be explained if we assume more wall pinning sites for rough underlayer than for smooth one, as Satoh et al. suggested[20]. Since a domain wall stops at a pinning site the mark shape tends to be polygon connecting the pinning sites. Thus the domain shapes become more irregular in the film with fewer pinning sites. Satoh et al. also presumed that the magnetization reversal process depends on the underlayer roughness because of the difference in the number and the force of the pinning sites, which are related with the recording characteristics.

In the present study we observed marks recorded with various values of the field opposite to that of normal recording in order to study the role of the underlayer roughness in forming the recorded marks.

![Mark Images](image)

**FIG. 4.** The mark images recorded on the smooth (a) and the rough (b) underlayers.

Figure 5 shows the mark images recorded under the various external fields from -400 to 0 Oe on the smooth underlayer (a), and the rough underlayer (b), and it also shows higher magnification images of marks on the rough underlayer (c). The minus sign indicates that field direction is opposite to that of normal recording, however, magnetization reversal occurs because of the
FIG. 5. The mark images of TbFeCo recorded in the zero or negative magnetic fields on the smooth underlayer (a), and the rough underlayer (b), and higher magnification images of marks on the rough underlayer (c).

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demagnetization fields. Apparently the process of the mark creation is different in (a) and (b). In (a) no domains are recorded at -150 Oe. When the strength of the external field decreases to -100 Oe small domains with distorted shapes are created, and the domains grow as the negative field decreases. At the 0 field the mark shapes almost reach their usual one although the sizes are still smaller. On the other hand, a number of small domains with a size of less than 0.1 μm appear at the negative field of -300 Oe in (b). It should be noted that the complete mark shape is already formed in the negative field of 200-300 Oe. The number of the small domains increases as the negative field decreases. This is clear in (c) with higher magnification. The images at -100 Oe show similar characteristics to the images reported by Satoh et al. which were taken by polarized optical microscope[20].

FIG. 6. The external field dependence of the carrier level of TbFeCo recorded on the rough and the smooth underlayers.

The relation of the carrier level of these media and the applied field was studied. Figure 6 shows the same tendency reported by Satoh et al. This is consistent with the result of the mark images. For both samples the carrier keeps almost constant when the mark images were recorded under the positive applied field. On the rough underlayer the carrier decreases gradually as the negative field increases and it reaches the noise level at -300 Oe. In contrast, on the smooth underlayer the carrier level decreases drastically around -50 Oe and reaches the noise level.

Given these results, the magnetization reversal process can be explained by using the assumptions of Satoh et al.[20] As for the case with the smooth underlayer as shown in Fig. 5 (a), in the higher negative field region than 150 Oe, no domains can be observed. One explanation for this is that tiny reversed multidomains, which have nucleated once during the thermomagnetic recording process, collapse instantaneously after the laser power beam goes away. This is because the force to shrink the domain overcomes the force to expand and wall-pinning force, where the force
to shrink and expand the walls comes respectively from the wall energy and the demagnetization energy. When the force to expand walls overcomes other forces during the laser heating in the higher field region, in our experiments the region of the negative field with less strength than 50 Oe, the reversed domains expand rapidly, positioning the walls to the pinning sites, and are stable after the laser heating. The number of the pinning sites should be small judging from the ragged shapes in the region of negative field of 50 Oe.

In Fig. 5 (b), on the other hand, tiny domains nucleating during the laser heating can exist stably after the laser heating due to the strong force of the pinning sites. It is difficult for the force to expand walls to overcome the pinning force, so the size of each domain does not grow largely as the negative field decreases, whereas the number of small domains increases. Thus it is reasonable to say that more pinning sites with stronger pinning force exist in this film than that in Fig. 5 (a). The small domains form the mark shapes at the field of -200 Oe, which does not become much larger as the field increases. The size of the recorded mark on this sample, therefore, is not sensitive to the external field, which is supposed to be due to the sharp decrease of the coercive force at the mark edge when it is thermomagnetically recorded[16]. To explain this insensitivity precisely, however, other factors - such as the demagnetization field from the close reversed domains or the spatial variation of the coercive force - must be taken into account.

The pinning force may be caused by the spatial variation of the magnetic parameters such as anisotropy due to the underlayer roughness, which is suggested by the simulation[18,19]. Further experiments are required to study the position where the domain walls are pinned on the uneven sample surface.

This difference in the magnetization reversal processes proves the difference in the number and intensity of the wall pinning sites as discussed above. On the smooth underlayer with fewer pinning sites, the mark shapes become irregular, while they are uniform on the rough underlayer with more pinning sites. We can assume that the domain wall pinning sites are needed to create the uniform mark shapes and to decrease the recording noise.

4. Conclusion

The recorded mark shapes of magneto-optical media TbFeCo were studied. In the marks on the land/groove substrate, we confirmed that the borders between lands and grooves prevent the expansion of marks to adjacent tracks. This effect is useful in land/groove recording because it reduces the effect of cross write. The magnetization reversal process depends on the underlayer roughness - as Satoh et al.[20] suggested - which is caused by the difference in the pinning effect. A large number of domain wall pinning sites are required to form uniform mark shapes and to reduce the recording noise.

Reference