Influence of Temperature and Mechanical Scratch on the Recorded Magnetization Stability of Longitudinal and Perpendicular Recording Media

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Abstract. Stability of recorded magnetization of hard disk drive (HDD) is influenced by external environments, such as temperature and magnetic field. Small scratches are frequently formed on HDD medium surface upon contacts with the magnetic head. The influences of temperature and mechanical scratch on the magnetization structure stability are investigated for longitudinal and perpendicular recording media by using a magnetic force microscope. PMR media remained almost unchanged up to about 300 °C for the area with no scratches, whereas the areas near and under mechanical scratches started to change around 250 °C. The magnetization structure of LMR media started to change at about 100 degrees lower temperature under mechanical scratches when compared with no scratch areas. A quantitative analysis of magnetization structure variation is carried out by measuring the recorded magnetization strength difference estimated from the MFM images observed for a same sample area before and after exposing the sample to different temperatures.

1. Introduction
The area density of hard disk drive (HDD) has been increasing through implementation of perpendicular magnetic recording. As the area density increases, stability of recorded magnetization is becoming an important research topic. Various studies have been carried out by using computer simulation [1,2], spin-stands [3,4] and magnetic force microscopes (MFMs) [5–7]. MFM is useful to directly observe the detailed variation of recorded magnetization structure. The stability of recorded magnetization will be influenced by several factors, such as temperature, magnetic field, stress, impact, etc. Increasing magnetic recording density requires lower flying height of head slider. A modern HDD generally requires head-disk spacing of less than 10 nm. With such a narrow spacing, small scratches are frequently formed on the medium surface upon contacts with the magnetic head. The influence of mechanical scratch on the magnetization of recording media has been studied for longitudinal [8,9] and perpendicular media [10–12]. In the present study, the influences of temperature and mechanical scratch on the recorded magnetization structure were investigated for longitudinal (LMR) and perpendicular (PMR) media under similar experimental conditions using a magnetic force microscope equipped with a heating stage. The magnetization stability was compared between PMR and LMR recording media.
2. Experimental procedure

A commercial LMR HDD disk with 120 Gb/in² area density, a PMR HDD disk with 120 Gb/in² area density, and a PMR HDD disk with 528 Gb/in² were used as the samples. The HDD disks were cut into small pieces to observe the magnetization structure under an MFM. Before cutting the disks, random data were recorded on the HDDs. Mechanical scratches were formed on the small piece sample with a diamond-coated cantilever using an atomic force microscope (AFM). The cantilever was moved along a line while applying an adequate force to form a mechanical scratch. The depth was controlled by adjusting the force. The sample surface was observed by using the AFM. The protective layer thickness of HDD disk sample was estimated by employing a reflectivity measurement using X-rays. The samples were then set on a heating stage in an MFM chamber which could be evacuated down to 10⁻⁴ Pa vacuum. The sample temperature was controlled in a range between room temperature (RT) and 300 °C. Same sample areas were observed with the MFM repeatedly after cooling the sample to RT.

3. Results and discussion

3.1. Formation of mechanical scratches

Figure 1 shows AFM images of LMR and PMR HDD disk samples with mechanical scratches. The bottom figures show the cross-sectional profiles of sample surface measured along the dotted lines shown in the upper figures. The depths are 15 nm and 5 nm for the two mechanical scratches (A and B) of the LMR medium. The protective layer thickness is estimated to be 6 nm by X-ray analysis. Figure 1(c-1), (d-1) and Figure 1(e-1), (f-1) respectively indicate the AFM images of PMR HDD disk samples (120 Gb/in² and 528 Gb/in²) with mechanical scratches. The depths are 12 nm, 3 nm, 14 nm, and 3 nm for the mechanical scratches of C, D, E, and F, as respectively shown in Figs. 1(c-2), (d-2), (e-2), (f-2). For both PMR samples, the protective layer thickness is estimated to be 5 nm. A deeper scratch is penetrating the protective layer and is causing some plastic deformation in the recording layer, while a shallow scratch is within the protective layer thickness.

**Figure 1.** AFM images of (a-1, b-2) LMR medium (120 Gb/in²), (c-1, d-1) PMR medium (163 Gb/in²), and (e-1, f-1) PMR medium (528 Gb/in²) with two mechanical scratches. Cross-sectional surface profiles measured along the respective dotted lines are shown in the lower figures (a-2, b-2, c-2, d-2, e-2, f-2).
3.2. Influence of temperature on the recorded magnetization

Figure 2(a-1)–(a-6) shows a series of MFM image observed for a same position area after exposing the LMR sample at elevated temperatures. The sample temperature was increased in a stepwise up to 300 °C. The duration of heating at respective temperature was kept nearly constant at 40 minutes. The MFM images were observed at RT by cooling from high temperatures to prevent sample drift at elevated temperatures. In the MFM images, the bright contrast corresponds to the area where a repulsive force is working between the MFM cantilever and the medium, while the dark contrast corresponds to the region where an attractive force is working. The magnetization structure of LMR sample is kept unchanged up to 200 °C. Magnetization structure variation is recognizable when the sample was heated at 250 °C as shown in Figure 2(a-5). It is notable, for example in the areas shown with dotted white lines, that the magnetization transition starts to shift parallel to the track direction. The magnetization transition profile is apparently different between the images shown in Figure 2(a-4) and (a-5).

Figures 2(b-1)–(b-6) and (c-1)–(c-6) respectively indicate the magnetization structure variations of PMR samples (120 Gb/in² and 528 Gb/in²). The low area density PMR sample is notable that the recorded bit shape starts to change when the sample was heated at 300 °C as shown in Figure 2(b-6), whereas the high area density PMR sample shows no variation.

3.3. Influence of temperature and mechanical scratch on the recorded magnetization

Figure 3 shows an AFM and a series of MFM images observed for a same area of LMR sample with mechanical scratches when the sample temperature was increased. Recorded magnetization structure is visible for the area under the shallow mechanical scratch of B, whereas it is apparently deformed under the deep scratch of A as shown in Figure 3(a-1). The recording layer under the deep scratch A is considered to have damaged where the depth is 15 nm and exceeds the carbon protective layer thickness. The AFM image (Figure 3(a)) shows the topological information of the disk surface while the MFM image (Figure 3(a-1)) shows the magnetic information. It is notable that the recorded bit shape near the shallow mechanical scratch starts to change at around 150 °C. The result suggests that
Figure 3. AFM and MFM images of LMR sample with mechanical scratches. (a) and (b) are the AFM images of the sample shown in Figure 1 for the areas of A and B, respectively. (1)-(6) are the MFM images of the areas corresponding respectively to the AFM images of (a) top row, (b) bottom row, observed after exposing the sample to (1) RT, (2) 100 °C, (3) 150 °C, (4) 200 °C, (5) 250 °C, and (6) 300 °C. The white dotted lines are added to indicate clearly the variations of magnetization structure.

Figure 4. AFM and MFM images of PMR sample (120 Gb/in^2) with mechanical scratches. (a) and (b) are the AFM images of the sample shown in Figure 1 for the areas of C and D, respectively. (1)-(6) are the MFM images of the areas corresponding respectively to the AFM images of (a) top row, (b) bottom row, observed after exposing the sample to (1) RT, (2) 100 °C, (3) 150 °C, (4) 200 °C, (5) 250 °C, and (6) 300 °C. The white dotted lines are added to indicate clearly the variations of magnetization structure.

Figure 5. AFM and MFM images of PMR sample (528 Gb/in^2) with mechanical scratches. (a) and (b) are the AFM images of the sample shown in Figure 1 for the areas of E and F, respectively. (1)-(6) are the MFM images of the areas corresponding respectively to the AFM images of (a) top row, (b) bottom row, observed after exposing the sample to (1) RT, (2) 100 °C, (3) 150 °C, (4) 200 °C, (5) 250 °C, and (6) 300 °C.
the mechanical stress caused by the scratch destabilizes the recorded magnetization.

Figure 4 shows an AFM image and the magnetization structure variation of PMR sample (120 Gb/in²) with mechanical scratches when the sample temperature was increased. The recorded magnetization structure is deformed under the scratch of C similar to the case of LMR medium sample (Figure 4(a-1)). From the series of MFM images shown in Figure 4, it is clear that the recorded magnetization structure starts to change noticeably near and under the mechanical scratches when the sample was heated at 250 °C. The temperature above which the recorded magnetization structure starts to change is lowered near the deep scratch and around the shallow scratch when compared with other normal areas for both types of media. The result suggests that a stress distribution around the scratch delicately influences the demagnetization behavior of recorded magnetization.

Figure 5 indicates an AFM image and the magnetization structure variation of PMR sample (528 Gb/in²) with mechanical scratches when the sample temperature was controlled in a range between room temperature and 300 °C. There is no variation in the area around the deep scratch E and the shallow scratch F of perpendicular magnetization for the medium with increased area density. The result indicates that the recorded magnetization of perpendicular medium tends to be stabilized with increasing the recording density.

3.4. Analysis of magnetization structure variation

The recorded magnetization variation is estimated from the MFM contrast intensity measured along the track centers. Examples are shown in Figure 6 and Figure 7. The analysis lines along the track...
center and the along upper track edge are shown as the white dotted lines in the respective MFM images. It is possible to estimate the bit shift caused by magnetic domain wall movement on heating. Bit shifts are apparently enhanced by the presence of mechanical scratches. When the LMR sample is exposed to 150 °C, the bit shift starts to be observed in the area near the mechanical scratch as indicated by an arrow. In the area with no mechanical scratch, the MFM intensity peak positions tend to move in the direction parallel to the recording track when the sample is exposed to 200 °C. When the magnetization variations are compared between near and under a scratch, it is notable that MFM contrast intensity variation tends to be observed more preferentially around the scratch fringes. The magnetization structure changes easily near the track edge rather than at the track center. Such influences are noted up to 45 nm distance from the scratch fringe as shown in Figure 7(b). For both media, the MFM contrast intensity became reduced and degraded at 300 °C.

4. Summary
Influences of temperature and mechanical scratch on the recorded magnetization structure of LMR and PMR media have been investigated using an MFM equipped with a heating stage. The magnetization structure starts to change at lower temperature in the area near and under the mechanical scratch when compared with a normal area with no scratch for both the LMR and PMR media with similar area density (120 Gb/in²). With increasing the area density of PMR medium, the magnetization structure is stabilized due to a decrease of demagnetization and shows no variation up to 300 °C. The recording layer under a mechanical scratch where the depth exceeds the carbon protective layer tends to lose the recorded magnetization structure, while that of under a shallow mechanical scratch less than the protective layer thickness tends to keep the recorded magnetization structure. The recorded magnetization stability decreases preferentially around the fringes of mechanical scratch.

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