MFM analysis of magnetic inhomogeneity in recorded area for perpendicular magnetic recording media by simultaneous imaging of perpendicular and in-plane magnetic field gradient

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Abstract. A new MFM method which can measure the perpendicular and in-plane magnetic field gradient simultaneously was developed. The measuring direction of in-plane magnetic field can be easily changed only by selecting the scanning direction of MFM tip with respect to the sample. This method was used to successfully estimate the magnetic domain structure of recorded area on CoCrPt-SiO₂ perpendicular magnetic recording media. When the scanning direction is along the down-track direction, the component of strong magnetic field gradient along the down-track direction can be observed with high spatial resolution at the bit transition. On the other hand, when the scanning direction is along the cross-track direction, the new MFM method is effective to mask the component of magnetic field from homogeneous recorded bits, and consequently the components of magnetic field from bended recorded bits at the track edge can be observed. The simultaneous measurement of perpendicular and in-plane magnetic field is useful to evaluate the magnetic inhomogeneity of recorded area such as bit transition and track edge.

1. Introduction
In order to analyse the microscopic magnetic domain structure of perpendicular magnetic recording media, magnetic force microscopy (MFM) vector imaging of perpendicular and in-plane magnetic fields with high spatial resolution is quite useful. However, the conventional MFM can only detect the gradient of a vector component of the magnetic field determined by the direction of the tip magnetization [1]. J. G. Zhu et al. proposed the imaging method for perpendicular and in-plane magnetic field gradient [2]. This method uses the change of MFM tip magnetization direction. Here, we showed that MFM tip coated by L10-FePt film, whose magnetized direction is strongly perpendicular to the sample surface due to its very large coercitivity, is very effective to obtain high spatial resolution image for very high density recording media. Therefore, the change of MFM tip magnetization direction is not effective to obtain high spatial resolution. We developed a new MFM
imaging method which can measure the perpendicular and in-plane magnetic field gradient simultaneously during the same scan by using the transient oscillation of a MFM tip coated by $L1_0$-FePt film [3]. It was showed that frequency change of MFM tip, which is occurred by the transient oscillation of the MFM tip, corresponds to the in-plane magnetic field gradient [4]. The measuring direction of the in-plane magnetic field gradient, which is the same as the scanning direction of the MFM tip, can be easily selected only by changing the scanning direction of the MFM chip. In this study, the perpendicular magnetic recording media were observed by using simultaneous imaging of the perpendicular and in-plane magnetic field gradient to analyze the magnetic inhomogeneity of the recorded area.

2. Experimental procedure
A phase locked loop (PLL: easyPLL, Nanosurf) circuit was used to measure the frequency shift of the MFM tip resonance in a conventional phase detection MFM. Here, the MFM tip was driven at a constant frequency near the resonant frequency of the MFM tip. The frequency shift of the MFM tip was only detected when the MFM tip has moved. The phase shift was measured after frequency shift disappeared. Therefore, the phase and frequency of the oscillation of MFM tip were measured at the same scan, though the phase and frequency shift were measured at the respective time. The MFM tip-sample distance was kept constant (15 nm) after the topographic scan by using the so-called “lift mode” measurement. We used a high-coercivity MFM tip with a coating of 20 nm $L1_0$-FePt film whose coercivity is about 8 kOe, which is made by Nitto Optical Co., Ltd. The magnetized direction of the MFM tip was perpendicular to the sample surface by applying a magnetic field of 18 kOe in advance. The MFM tip with high coercivity is effective to suppress the oscillation of its magnetization, and consequently to obtain microscopic magnetic domain images with high spatial resolution.

The CoCrPt-SiO$_2$ perpendicular magnetic recording media were observed, which was prepared by using an in-line-type magnetron sputtering system. Transmission electron microscopy showed CoCrPt nanograins with an averaged diameter of 5.9 nm and an average intergranular distance of 1.6 nm. Recording signals (50 or 500 or 1000 kfcf) were written by using a perpendicular single-pole inductive head. The MFM measurement was done in vacuum atmosphere. The value of Q was in the range from 6000 to 8000. The resonant frequency of MFM tip was 280-320 kHz.

3. Results and Discussions
Figure 1 (a) shows the MFM images of a CoCrPt-SiO$_2$ perpendicular magnetic recording media with the recorded linear density of 50 kfcf measured by the conventional phase detection method, and (b) shows the MFM image measured by the presented frequency detection method. The images of Figs. 1 (a) and (b) were measured at the same scan position from left to right in horizontal direction. Figs. 1 (c) and (d) show the signal profiles of the lines in image (a) and image (b). The phase detection image (a) and its corresponding signal profile (c) are well characterized as those of the perpendicular magnetic field gradient. The areas of up and down magnetizations with respect to the sample plane show the bright and dark contrasts. The boundaries between up and down magnetization areas show the neighboring bright-dark contrast. On the

![Figure 1. Phase detection image (a) and frequency detection image (b) for a CoCrPt-SiO$_2$ perpendicular magnetic recording media. Signal profiles (c) and (d) on the line in image (a) and (b) of the perpendicular magnetic recording media.](image-url)
other hand, the frequency detection image (b) and its corresponding signal profile (d) are well characterized as those of the in-plane magnetic field gradient, and show the neighboring bright-dark-bright and dark-bright-dark contrasts at the boundaries. In the case of perpendicular magnetic recording media, the maximum and minimum intensities of the in-plane field gradient are obtained at the boundaries of neighboring recorded bits where the intensities of the perpendicular field gradient is zero. This indicates that frequency detection method is effective to observe the magnetic fluctuation at recorded bit transition. Figure 2 (A) shows (a) phase detection image and (b) frequency detection image of the CoCrPt-SiO$_2$ perpendicular magnetic recording media with the recorded linear density of 500 kfc/ and their spatial resolution results. The spatial resolution is defined by the value of $k_x$ at which MFM signal intensity becomes same level as noise intensity, as shown by arrows. The spatial resolution of the in-plane magnetic field gradient measured by the new MFM method was 9.1 nm, nevertheless the case of the perpendicular magnetic field gradient measured by same scan with conventional phase detection method was 9.5 nm. This indicates that frequency detection method is effective to observe the magnetic domain structure with high resolution.

Figure 2 (B) shows the simulation results of MFM resolution for (a) phase detection image and (b) frequency detection image. A quadrilateral pyramid is used as the MFM tip shape in this simulation, which was observed by using SEM. The spatial resolution of the in-plane magnetic field gradient measured by the new MFM method was 10.0 nm, nevertheless the case of the perpendicular magnetic field gradient measured by the conventional phase detection method was 10.5 nm. The simulation results agree with experimental data.

From these results, it can be said that the frequency detection method is helpful to analyze the magnetic inhomogeneity of recorded bits with high resolution.

Figures 3 (A) (a) - (c) and (d) - (f) show the images of perpendicular and in-plane magnetic field gradient for the CoCrPt-SiO$_2$ perpendicular magnetic recording media with the recorded linear density of 500 kfc/ with the scanning angle $\theta$ of 0 ((a), (d)), 45 ((b), (e)), and 90 ((c), (f)) degree. Here the $\theta$ is assumed angle between the scanning direction (from the left side to the right side in the images) and the down-track direction. The clear contrast of perpendicular magnetic field gradient at the recorded bits is observed among each $\theta$. However, the contrast of in-plane magnetic field gradient at the recorded bits decreases with the increasing $\theta$.

Figure 2. (A) MFM images and its spatial resolution results of (a) phase detection and (b) frequency detection method. (B) Simulation results of MFM resolution for the (a) phase detection and (b) frequency detection image. The arrows indicate the spatial resolution which is defined by the value of $k_x$ at which MFM signal intensity becomes the same as noise level.
In the case of $\theta = 0$ degree (scanning direction is parallel to the down-track direction), largest signal intensity is obtained. With the increasing $\theta$, the signal intensity decreases following the $\cos(\theta)$ curve (dotted line). In the case of $\theta$ of more than 75 degree, the signal intensity becomes constant. These results indicate that signal output corresponds to the in-plane magnetic field gradient along with the scanning direction, and signal output with $\theta$ of around 90 degree is due to media noise. It can be said that the in-plane magnetic field gradient with the scanning angle of $\theta = 90$ degree is effective to mask the ideally recorded signal.

Figure 4 shows (a) the perpendicular magnetic field gradient image and (b) in-plane magnetic field gradient image obtained by the same scan for CoCrPt-SiO$_2$ perpendicular magnetic recording media with the recorded linear density of 500 kfc. The recording angle $\theta$ is 90 degree (scanning direction is along the cross-track direction.). The recorded bits can be clearly observed by the conventional imaging as shown in Fig. 4(a), while, they cannot be seen from Fig. 4(b). However, the in-plane magnetic field imaging detects the bended recorded bits around the track edges. Moreover, the magnetic contrast is observed in the recorded area. If the recorded patterns have no media noise, no magnetically contrast can be observed in the recorded area. Therefore, the imaging method seems to be effective to mask homogeneous magnetic field from recorded bits and to observe magnetic inhomogeneity in recorded area as can be seen in Fig. 4(b).
From these results, the present simultaneous imaging of perpendicular and in-plane magnetic field gradient with high spatial resolution is useful to evaluate the magnetic inhomogeneity of recorded area for high-density perpendicular magnetic recording media.

4. Conclusions
The simultaneous measurement of the perpendicular and in-plane magnetic field gradient for perpendicular magnetic recording media was examined by using a new MFM method which detects the transient oscillation of a tip. The obtained results can be summarized as follows:
(1) The in-plane magnetic field gradient detection method is effective to observe the recorded bit transition when the scanning direction is parallel to the down-track direction.
(2) The spatial resolution of the in-plane magnetic field gradient measured by the new MFM method is higher than the case of the perpendicular magnetic field gradient measured by the same scan with conventional MFM method.
(3) The in-plane magnetic field gradient detection method is effective to mask the component of homogeneous magnetic field from recorded bits, and to observe the bended magnetic field from recorded bits at the track edges when the scanning direction is along the cross-track direction.
(4) The simultaneous measurement of perpendicular and in-plane magnetic field is effective to evaluate the magnetic inhomogeneity of recorded area.

5. References
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