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<Paper>

AC Magnetic Field Imaging of Perpendicular Magnetic Write Head without Image Distortion on Alternating Magnetic Force Microscopy using a Cone-Shape FePt-coated Tip

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The AC magnetic field of a perpendicular magnetic write head having three surrounding shields was successfully imaged without image distortion on our alternating magnetic force microscope (A-MFM) using a newly developed cone-shape Si tip coated with an $L1_0$-FePt film. In contrast, a conventional quadrangular pyramidal Si tip coated with the $L1_0$-FePt film showed a distortion of the AC magnetic field image for the same magnetic write head. The image distortion depended on the spatial configuration between the tip and the write head. It is concluded that a round magnetic symmetry of the cone-shape FePt-coated tip is most effective for taking a clear AC magnetic field image of the perpendicular magnetic write head having three surrounding shields without distortion.

Key words: perpendicular magnetic write head, alternating magnetic force microscopy, image distortion, cone-shape FePt-coated tip

1. Introduction

In perpendicular magnetic recording, the demand for high magnetic recording density requires the super performance of magnetic recording media and magnetic write/read head. To achieve high recording density, the write head design has to be optimized to achieve the large field magnitude and a high field gradient in both the down-track and cross-track directions as required. So far, most characterizations of the magnetic field of write head have been done by theoretical modeling[1)-4)]. However, the simulation of the exact working conditions of a write head in a drive has encountered difficulty when using theoretical modeling. At the same time, the characterization of write head has been done by experimental spin-stand measurements. The results obtained from this spin-stand measurement not only include the effect of the real magnetic field distribution of the write head, but also the magnetic property and microstructure of the recording media.

Magnetic force Microscope (MFM) is a powerful tool to understand the microscopic magnetic domain/bit structures of high density magnetic recording media and nanoscale magnetism[5)]. The maximum resolution of an MFM is approximately 10 nm[6)]. For this reason, MFM applications for the development of magnetic materials and magnetic devices have received more and more attention over the past ten years.

To detect and image an AC magnetic field, the conventional MFM has to employ a frequency which is close to the mechanical resonant frequency of the MFM cantilever[7),8)]. Because the cantilever acts as a mechanical filter near its resonant frequency, the signals at the frequencies that are not close to the cantilever's resonant frequency will not be picked up.

In our previous work, we have developed a new MFM to image AC magnetic field with a wide frequency range that is referred to as alternating magnetic force microscopy (A-MFM)[9)]. The A-MFM uses a frequency modulation (FM) of the cantilever oscillation by applying an AC magnetic field over it. The A-MFM can measure the vertical component of an AC magnetic field when the magnetization direction of MFM tip is perpendicular to the sample surface. Previously, we achieved high-resolution AC magnetic field images for a perpendicular magnetic write head having a one-side trailing shield by such A-MFM with a conventional quadrangular pyramidal FePt-coated tip[10),11)]. The $L1_0$-FePt film having a coercivity of more than 10 kOe has been used for the MFM tip in this case, because the magnetic field from the write head is overly strong to be able to change magnetization of an MFM tip. The development of MFM tips coated with hard magnetic materials such as Fe-Pt[12)-16)], Fe-Pd[16),17)], Co-Pt[18)-22)], and Sm-Co[23)] were reported by several groups. However, the shape effect of the MFM tip with hard magnetic coatings has barely taken into account.

In the present study, we developed a new FePt-coated tip with a special shape for the characterization of a perpendicular magnetic recording head having three surrounding shields. The head design having three surrounding shields can generate more focused magnetic field for high recording density. The conventional quadrangular pyramidal shape tip with FePt coating usually causes image distortion for this type of head. The newly-developed tip was supposed to fix the issue with the image distortion of the AC magnetic field. The image distortion is defined as the disaccord between the position, shape, and spatial symmetry of main pole in topographic image and those of strong signal in amplitude image of A-MFM. We analyzed the cause for the image distortion of the AC magnetic field when using the quadrangular pyramidal-shape tip and found the way to make the AC magnetic field successfully imaged without distortion by using the developed FePt-coated tip. In this paper, we will also show a necessity to increase the coercivity of hard magnetic coating to characterize future perpendicular magnetic write head.

2. Experimental Procedure

The A-MFM was built from a conventional scanning probe microscope (JSPM-5400 (JEOL Ltd.) and/or SPI3800N･SPA300HV (SII-NT Ltd.)). All of the measurements were done in air atmosphere. The cantilever was oscillated by using a piezoelectric element. The value of the resonant frequency of the cantilever with the MFM tip was approximately 330 kHz. The oscillation frequency (f_c) of the piezoelectric element was set at 325 kHz which is close to the resonant frequency of the tip, and the value of Q was around 500.

A perpendicular magnetic write head having a one-side trailing shield and a perpendicular magnetic write head having three surrounding shields were sampled for this work. The write head was driven by a sinusoidal AC current with a zero-to-peak amplitude of 20 or 40 mA at the frequency (f_m) of 100 Hz.

The AC magnetic field frequency modulated the cantilever resonant frequency. The cantilever deflections were sensed by using laser beam deflection. The AC magnetic field measurement was achieved by the lift mode after topographic measurement. The lift height was 10 nm. The amplitude and phase information of the alternating force between the sample and the tip was extracted by using a lock-in amplifier where the input signal was the frequency demodulated signal of cantilever oscillation from a phase-locked loop (PLL) circuit and reference signal was the frequency signal of f_m from signal generator8),9).

Both conventional high-coercivity MFM tip (SI-MF40-Hc, Nitto Optical Co. Ltd.) with a quadrangular pyramidal shape (DF-40, SII Co. Ltd.) and a 30 nm-thick $L1_0$-FePt coating, and a new made-in-house MFM tip in cone-shape (SS-ISC, Team Nanotec Co. Ltd.) coated with the same thickness $L1_0$-FePt film were used in this work. The MFM tips were magnetized to saturation along the tips axis before use to make sure the magnetization direction of the tips were vertical to the write head surface.

3. Results and Discussions

First, the quadrangular pyramidal FePt-coated tip was used to take the amplitude and phase images of the AC magnetic field of the two types of write heads. Fig.1 shows SEM images of the quadrangular pyramidal Si tip. Fig.1 (a) is an image of entire tip, Fig.1 (b) a magnified image of the vertex region of the tip, and Fig.1 (c) a top view of the vertex region of the tip.

The results for the head having a one-sided trailing shield and the head having three surrounding shields are shown in the topographic image in Fig.2 (a) and (d), respectively. Fig.2 (b) and (c) are the amplitude and the phase images of the AC magnetic field for the head having a one-sided trailing shield, respectively. Fig.2 (e) and (f) are the amplitude and phase images for the head having three surrounding shields, respectively. In all measurements the AC current was fixed at 20 mA.

For the head having a one-side trailing shield, the amplitude and the phase images of the AC magnetic field are clearly observed without distortion. In Fig.2 (b), the strong amplitude of the AC magnetic field (bright area) appears at the main pole position. In addition, a relatively large field intensity is obtained at the trailing shield position near the gap, and a very low intensity of near-zero is obtained at the gap position. In Fig.2 (c), the polarity of the field can be clearly observed as a binary image. The phase difference between the dark area and bright area is approximately 180°. If the dark area corresponds to the in-phase magnetic field with respect to the head current, the bright area corresponds to the field in the opposite direction. As shown in this figure, the polarity of the perpendicular component of the AC magnetic field at the main pole region and the trailing shield region of the head can be clearly distinguished. The AC magnetic field images were clearly observed without obvious distortion for the write head having a one-sided trailing shield.

In contrast, the image of the strong amplitude of the AC magnetic field (bright area) around the main pole position becomes asymmetric on certain direction

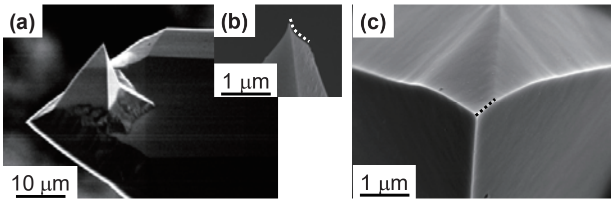

Fig. 1 SEM images of quadrangular pyramidal Si tip: (a) entire tip, (b) magnified image of vertex region of the tip, and (c) top view of vertex region of the tip. The dotted line in (b) and (c) indicates the ridges from the 1st vertex to the 2nd vertex of the tip.

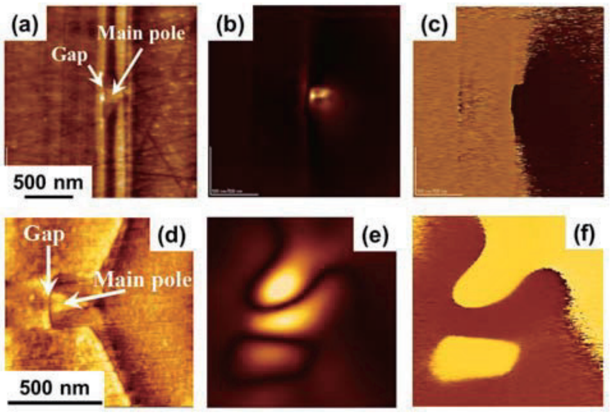

Fig. 2 (a) and (d) are topographic images, (b) and (e) are amplitude images of the AC magnetic field, and (c) and (f) are phase images of the AC magnetic field. (a), (b), and (c) are images for the write head having a one-sided trailing shield, and (d), (e), and (f) are images for the write head having surrounding shields on three sides.

as shown in Fig.2 (e). In addition, a near-zero intensity is not observed at the gap position. In Fig.2 (f), the polarity of the field observed around the main pole position is also asymmetric in certain direction. A polarity change of the field could not be observed at the gap position.

The observations above hints at a distortion of the amplitude and the phase images for a head having three surrounding shields. To investigate the cause for the distortion of the AC magnetic field images, the shape effect of the quadrangular pyramidal FePt tip was taken into account. This tip has two vertices, and the dot line in Fig.1 (b) and (c) indicates the ridge line formed by the 1st vertex and the 2nd vertex of the tip. This ridge line is one possible factor contributing to the image distortion, the ambiguity at the gap position, and the asymmetry of the field images.

To clarify the influence of the ridge line of the tip on the AC magnetic field imaging, the spatial configuration between the quadrangular pyramidal FePt-coated tip and the write head having three surrounding shields was adjusted and imaged the AC magnetic field images. Fig.3 (a), (d), and (g) show schematics of the quadrangular pyramidal FePt-coated tip and the spatial configurations against the write head. The dotted line and bold line in (a), (d), and (g) indicate the outline and the ridge line formed by the 1st vertex and the 2nd vertex of the tip, respectively. Fig.3 (b), (e), and (h) show the corresponding amplitude images of the AC magnetic field, and Fig.3 (c), (f), and (i) show the corresponding phase images of the AC magnetic field for the write head. In the case of Fig.3 (g), the direction of the ridge line (bold line) is parallel to the direction of the cross-track of the write head. The (h) amplitude and (i) phase images of the AC magnetic field extend toward the direction of the cross-track of the write head. These results suggest that the image distortion of the AC magnetic field depends on the spatial configuration between the tip and the write head. Here, the (e) amplitude and (f) phase images of the AC magnetic field were already discussed in Fig.2 (e) and (f).

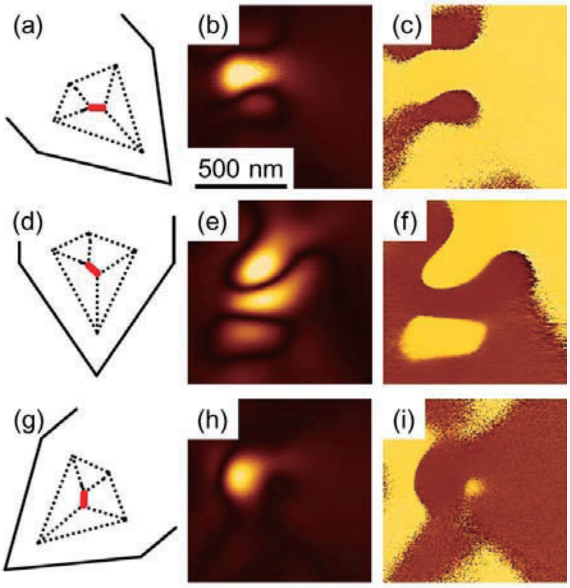

Fig. 3 (a), (d), and (g) are the schematics of the quadrangular pyramidal FePt tip and its spatial configuration against the writing head, (b), (e), and (h) are the amplitude images, and (c), (f), and (i) are the phase images of the AC magnetic field for the writing head having three surrounding shields.

Self-magnetic charge of the FePt film happens at the edge line of film surface. As a result, the magnetic pole line is created at each ridgeline of the tip and the center part of the tip end. The center part of the tip end mainly contributes to the signal for the AC magnetic field image in direction perpendicular to the ridge line of the tip, while the ridge lines of the tip mainly generate the signal for the AC magnetic field image in direction parallel to the ridge lines of the tip.

In order to reduce the influence of ridge pole line on imaging AC magnetic field, a new tip having a cone-shape was developed. Fig.4 shows SEM images of the cone-shape Si tip. Fig.4 (a) is the image of the entire tip, (b) is the magnified image of the vertex of the tip, and (c) is the top view of the vertex of the tip. This tip has only one vertex with a round symmetry. Within this cone-shape tip, the magnetic pole of FePt film forms only at the end of the tip. To see the influence of the improved round symmetry of the tip magnetics on the image distortion, the cone-shape FePt-coated tip was used for the characterization of the write head having three surrounding shields. Fig.5 show (a) a schematic of the cone-shape FePt-coated tip and its spatial configuration against the write head, (b) the topographic image, and (c) the amplitude and (d)

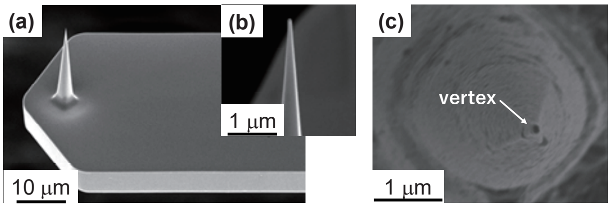

Fig. 4 SEM images of the cone-shape Si tip: (a) image of entire tip, (b) magnified image of vertex region of the tip, and (c) top view of vertex region of the tip.

phase images of the AC magnetic field of the write head having three surrounding shields. The dot line and bold point in (a) indicate the outline and the end point of the tip, respectively. The amplitude and the phase images of the AC magnetic field are clearly observed without image distortion. In Fig.5 (c), a strong intensity, relatively large intensity, and very low intensity of nearly zero can be seen at the main pole position, the trailing shield position near the gap, and the gap position, respectively. In Fig.5 (d), the polarity of the field can be observed clearly. The phase difference between the main pole and the three surrounding shields is approximately 180°. It is clear that the amplitude and phase images of the AC magnetic field are not distorted for the write head having three surrounding shields.

As described earlier, there was no image distortion observed for the head having one-side trailing shield by using the quadrangular pyramidal FePt-coated tip. The magnetic field of the head having one-side trailing shield is not strong enough compared with that of the head having three surrounding shields, and mainly focuses at the 1st vertex region of the tip. Moreover, the shape of the quadrangular pyramidal tip around the 1st vertex has a near-cone shape from the detail SEM observation. Therefore, the MFM measurement of the write head having one-side trailing shield by using the quadrangular pyramidal FePt-coated tip is almost same situations as that of the write head having three surrounding shields by using the cone shape FePt-coated tip. On the other hand, the magnetic field of the head having three surrounding shields focuses not only at the 1st vertex region but also the ridgeline of the quadrangular pyramidal tip. This is why the AC magnetic field image of the write head having three surrounding shields shows no distortion when using the cone-shape FePt-coated tip. This means that the MFM tip with round symmetry for the magnetic pole charge is very important to reduce image distortion when characterizing strong, widely-spread magnetic field generated from a write head. These results generally indicate that the MFM tip with asymmetry for the magnetic charge is effective to get a MFM image without distortion only for the case of samples which generate the not so strong and widely-spread magnetic field.

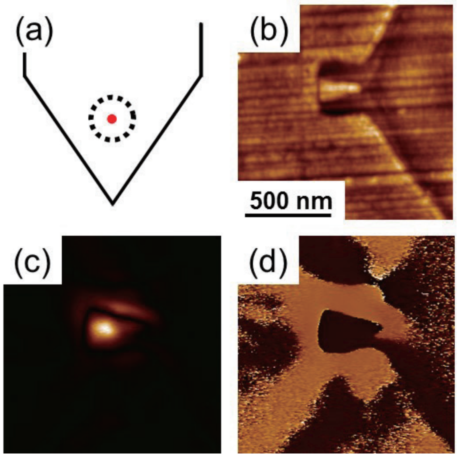

Fig. 5 (a) is a top view of the cone-shaped FePt tip, (b) is a topographic image, (c) is an amplitude image, and (d) is a phase image of the AC magnetic field for the write head with three surrounding shields.

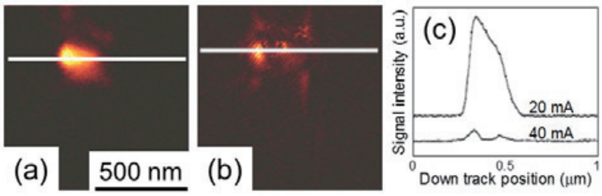

Fig. 6 (a) and (b) are the amplitude images of AC magnetic field for the write head having three surrounding shields at the head driving current of 20 mA and 40 mA, respectively. (c) is the down track line profile of amplitude signal of the white line shown in (a) and (b).

A sinusoidal AC current of 20 mA with a zero-to-peak amplitude was used for the above A-MFM characterization of the magnetic write head. This is smaller than that of the actual motion of magnetic write head working in hard disk drive.

Fig.6 (a) and (b) show the amplitude images of AC magnetic field taken by the cone-shape FePt-coated tip with a film thickness of 40 nm for the write head having three surrounding shields. In this run, the head driving current of 20 mA and 40 mA were applied respectively. Fig.6 (c) is the down track line profile of amplitude signal of the white line shown in Fig.6 (a)

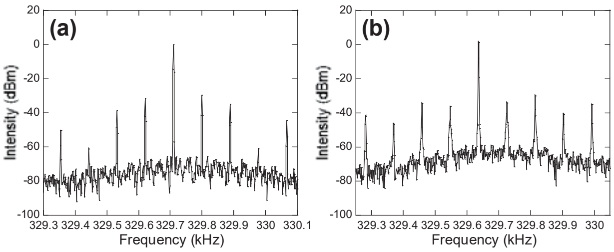

Fig. 7 Spectra of the cantilever oscillation with the head current of (a) 20 mA and (b) 40 mA.

and (b). The amplitude image (a) and its line profile for the head current of 20 mA were clear with a high amplitude signal at the main pole position. In comparison, the amplitude image (b) and its line profile for the head current of 40 mA were unclear and very low amplitude signal at the main pole position. Especially, there is an amplitude signal of near-zero with the head current of 40 mA at the position which has the highest amplitude signal with head current of 20 mA. These indicate that the magnetization state of the magnetic tip is different between the head currents of 20 mA and 40 mA.

To understand the difference of signal intensity with different head running currents, the measurement of frequency spectra of tip oscillation for each head current was carried out by using spectrum analyzer. Fig.7 (a) and (b) show the spectra of the tip oscillation with the head running current of 20 mA and 40 mA, respectively. The oscillation frequency (f_c) of the tip was 329.71 kHz (on the head current of 20 mA) and 329.64 kHz (on the head current of 40 mA), and the frequency (f_m) of the AC magnetic field 100 Hz. As seen in the figures, the sideband spectra with the frequency of $f_c \pm nf_m$ (n: an integer), which is modulated by AC magnetic field from head, are observed near the baseband spectra of the cantilever oscillation with the frequency of fc. The frequency of $f_c \pm f_m$ is dominating when coercivity of the magnetic component of tip is higher than the AC magnetic field. And the frequency of $f_c \pm 2f_m$ is dominating when coercivity of the magnetic component of the tip is smaller than the AC magnetic field. This is because, the spectrum intensity at $f_c \pm f_m$ is proportional to the gradient of magnetic field component which is perpendicular to the sample surface[9], and this indicates that direction of tip magnetization does not change when the $f_c \pm f_m$ is dominant. In Fig.7 (a), the modulated frequency with highest peak of the spectra was $f_c \pm f_m$. This indicates that hard magnetic behavior of the magnetic tip is dominant in the case of head current of 20 mA. By comparison, the modulated frequency with highest peak of the spectra was $f_c \pm 2f_m$ as shown in Fig.7 (b). This indicates that soft magnetic behavior of the magnetic tip is dominant in the case of head current of 40. The reason for the low amplitude signal at the main pole position in Fig.6 (b) is due to the increment of oscillation intensity at modulated frequency of the $f_c \pm 2f_m$. In addition, the modulated frequencies of $f_c \pm nf_m$ (n>2) were observed in both cases with different intensities. This suggests that the magnetization direction of the FePt tip sways in a non-linear way. It is clear that the coercivity of the FePt coating is lower than the magnetic field generated by the head with the current of 40 mA. The magnetization direction of the FePt tip is swayed by the magnetic field of the head with the current of 20 mA although the coercivity of FePt coating is larger than the head field. Therefore, the increase of tip coercivity is necessary to take accurate MFM images of future magnetic write head. We will describe the effect of increased tip coercivity in a future paper.

4. Conclusion

We analyzed the cause of the MFM image distortion of the AC magnetic field for the magnetic recording heads having 3 surrounding shields by comparing a conventional quadrangular pyramidal FePt-coated tip with our newly developed cone shape FePt-coated tip. The cone shape FePt-coated tip makes it able to image the AC magnetic field of perpendicular magnetic write head having three surrounding shields without image distortion.

In comparison to the quadrangular pyramidal shape structure of the conventional FePt tip, the cone-shape FePt-coated tip and its round magnetic symmetry are very effective in imaging the AC magnetic field of the write head having three surrounding shields without image distortion. In addition, it is necessary to increase the coercivity of hard magnetic coating in order to characterize the very high magnetic field for the future magnetic write head.

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