High coercivity and resolution FePt•MgO-coated tip for imaging the magnetic field of perpendicular magnetic write head by alternating magnetic force microscopy (A-MFM)

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High coercivity FePt•MgO films were successfully synthetized on cone-shape Si tips in a very high frequency (VHF) plasma irradiation-assisted magnetron sputtering system to prepare the MFM tips for evaluation of the AC magnetic field of perpendicular magnetic write head at high write current. Alloying with MgO significantly enhanced the coercivity of the magnetic coating due to the isolation of FePt grains by MgO. As a result, a high coercivity close to 20 kOe was achieved. The AC magnetic field images of the perpendicular magnetic write head at high write current were taken on alternating MFM (A-MFM) by this tip. A clear amplitude image with a strong signal at the main pole position was observe compared to the pure FePt layer-coated tip, which gave a blurry image and very small amplitude. Fourier analysis of the images obtained by this kind of FePt•MgO tip gives a spatial resolution of about 15 nm in air atmosphere. It is clear that the cone-shape FePt•MgO coated MFM tip with a coercivity higher than the magnetic field to be measured is effective and capable for measuring the high AC magnetic field for an HD perpendicular magnetic write head at a very high write current.

Key words: high coercivity and high resolution FePt•MgO-coated tip, very high frequency (VHF) plasma irradiation, perpendicular magnetic write head, alternating magnetic force microscopy (A-MFM)

1. Introduction

Magnetic force microscopy (MFM) is an effective scanning probe for investigation of the magnetic domain structures of magnetic materials in nanoscale such as magnetic recording media because of its high spatial resolution of the static magnetic field¹. The MFM tip is the most important key element to detect and image the surficial magnetic signal of an object. A high coercivity magnetic tip is one of the essential parameters for MFM imaging. Commercially-available MFM tip is usually an atomic force microscopy (AFM) tip coated with a thin CoCrPt film. There have been many efforts to prepare MFM tips such as synthetic antiferromagnetic coating with sandwich structures²³⁴, focused ion beam (FIB) trimming⁵⁶, carbon nanotubes coated with magnetic films⁷⁸, hard magnetic coatings of Fe₃Pt⁹¹⁰, Fe₃Pdt¹¹,¹², Co₃Pt¹³⁻¹⁸, Sm-Co¹⁹ were used for the preparation of MFM tips to image large magnetic field. In addition to the MFM tip, the methodology of MFM itself is also critical. We have developed a new MFM imaging method for characterization of AC magnetic field. We named it as alternating MFM (A-MFM)²⁰. The A-MFM uses a frequency modulation (FM) of the cantilever oscillation by applying an AC magnetic field on a mechanically oscillated tip. This can allow us to measure the perpendicular component of the AC magnetic field with respect to the sample surface. Previously, we used in-house-coated FePt tips with high-coercivity to image the AC magnetic field of a perpendicular magnetic write head having a one-sided trailing shield on our A-MFM set up²²,²³,²⁵. The spatial resolution was estimated to be 15 nm (a lift height of 1 nm and AC current with a zero-to-peak amplitude of 20 mA). However, this tip failed to characterize the AC magnetic field of the head having three surrounding shields when a large write current which generates a large magnetic field bigger than the coercivity of the FePt coating on the tip. To estimate the distribution of magnetic field from the head having three surrounding shields, MFM tip with symmetry shape for the magnetic charge and with high coercivity magnetic film is effective. We had reported the cone-shaped MFM tip with symmetry for the magnetic charge to get a MFM image without distortion²⁴. We also had reported that coercivity of the FePt coated MFM tip is lower than the magnetic field generated by the head having three surrounding shields with large head current²⁴. We deposited FePt•MgO films on the tip by VHF plasma irradiation-assisted magnetron sputtering in order to increase the coercivity of magnetic FePt film. The MgO²³ was used for isolation of FePt grains. The VHF plasma irradiation enhanced the L₁₀ FePt phase during sputtering²⁶. The new FePt•MgO MFM tip with very high coercivity was used for observation of AC magnetic image of perpendicular magnetic write head in this work.
FePt·MgO films with the total thickness of 20 nm were prepared onto Si substrates which had thermally-oxidized surface for the purpose to check their structure and magnetic properties. The FePt·MgO films were deposited in two different paths: one path was to sputter a composite target where many pieces of thin MgO plates were placed on the top of a Fe50Pt50 target; another path was to co-sputter both Fe50Pt50 and MgO targets. The volume fraction (Vol.%) of MgO in the final film was adjusted by changing the numbers of MgO thin plates on the Fe50Pt50 target, the sputtering power, and/or the target-to-substrate (T-S) distance. During the sputtering, the VHF plasma irradiation \(40.68\) MHz was fixed at \(40.68\) MHz with the electric power (PVHF) of 5 ~ 20 W as shown in Fig. 1. After sputtering, the FePt·MgO films were annealed at \(750\) ℃ in a rapid thermal annealing (RTA) system for 10 minute. The crystalline characteristics of the films were analyzed by x-ray diffraction (XRD). The magnetic properties were measured by a vibrating sample magnetometer (VSM). The made-in-house MFM tips with a cone-shaped Si tip (SSISC, Team Nanotec Co. Ltd.) consisted of a very thin SiO2 layer formed by plasma oxidation and a layer of the magnetic FePt·MgO (20 - 40 nm) film which were prepared under the same sputtering and post-annealing conditions. SiO2 layer was used to prevent interdiffusion between the magnetic film and Si tip. Before measurement, the MFM tips were magnetized to saturation along the tips axis, which means that the magnetization direction of the tips was vertical to the sample surface.

The A-MFM runs were carried out based on a conventional scanning probe microscope (JSPM-5400 (JEOL Ltd.)) in an air atmosphere. Figure 2 shows a scheme of the A-MFM. A lock-in amplifier and a phase-locked loop (PLL) circuit were used for the AC magnetic field measurement in the A-MFM. The cantilever was oscillated by using a piezoelectric element. The resonant frequency of the cantilever with the MFM tip was approximately 256 kHz. The oscillation frequency (\(f_0\)) of the piezoelectric element was about 250 kHz which is close to the resonant frequency of the tip, and the value of Q was around 500. The AC magnetic field was measured on the lift mode after topographic characterization. The lift height was 8 nm or 1 nm. The good spatial resolution was obtained at the lift height of 1 nm.

An advanced perpendicular magnetic write head having three surrounding shields was used for evaluation. In comparison with the magnetic write head having a one-sided trailing shield, this kind of write head can generate focused magnetic field for high recording density. The write head was run by a sinusoidal AC current with a zero-to-peak amplitude of 20 - 40 mA and a frequency (\(f_m\)) of 100 Hz.

3. Results and Discussions

Figure 3 shows \(\theta\)-2\(\theta\) XRD patterns of FePt, and FePt·MgO (16 Vol.% MgO) films without/with VHF plasma irradiation power of 15 W. All of the films show strong FePt(111) peak, which means the deposited FePt-based films have preferred (111)-texture. Due to the lowest interfacial energy of FePt(111) plane, the FePt film deposited on amorphous SiO2 substrate can have a

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**Fig. 1** Schematic image of VHF irradiation assisted ultra-high vacuum sputtering system.

**Fig. 2** Schematic of A-MFM system.

**Fig. 3** \(\theta\)-2\(\theta\) XRD patterns of FePt and FePt·MgO films.
(111)-favor texture growth. In Fig. 3 you cannot see a clear (001) peak, but the sputtering film with VHF plasma irradiation shows an enhanced (111) peak intensity, compared to the films without VHF plasma irradiation. The integral intensity of FePt(111) was 4853, 5155, and 6763, for the films of FePt, FePt-MgO, and FePt-MgO with VHF plasma, respectively. In our previous study\(^{26}\), a VHF plasma irradiation during sputtering deposition can effectively accelerate crystallization and atom ordering. It is believed that the VHF plasma irradiation can also accelerate the crystallization and ordering of L1\(_0\) FePt phase. As we know, the high magnetic anisotropy of FePt films can be obtained in the chemically ordering state, which can lead to high coercivity.

An in-plane easy axis of magnetization of the magnetic coating on is preferred for MFM tip preparation. Figure 4 shows the dependence of the in-plane coercivity of FePt-MgO films on the volume fraction of MgO. The inset shows hysteresis loops of FePt and (FePt)\(_{84}\)(MgO)\(_{16}\) film (in Vol.%), respectively. The coercivity rises from 9.2 kOe to 17.0 kOe when MgO's volume percentage in FePt-MgO film increases from 0 to 35 Vol.%. It is obvious that MgO addition to the FePt film significantly enhance the coercivity of the film. This is believed that the MgO's effect of isolation of FePt grains attributes to increased coercivity like the other kinds of element additives such as SiO\(_2\)\(^{27}\), C\(^{28}\), TiO\(_2\)\(^{29}\),\(^{30}\) added to FePt-base films.

Figure 5 shows the in-plane coercivity of FePt-MgO films versus the VHF plasma irradiation power. The inset shows hysteresis loops of (FePt)\(_{84}\)(MgO)\(_{16}\) film with VHF plasma irradiation power of 15 W. As shown in the figure, the coercivity gradually increases from 14.5 kOe to 15.9 kOe when VHF power changes from 5 W to 15 W. And then coercivity drops to 15.2 kOe as VHF power goes up to 20 W. The VHF bias is considered to have two effects: 1) the enhancement of atoms/molecules' mobility for ordering and 2) the ion bombardment on film during sputtering. The effect 1) of VHF bias is taking place to increase coercivity when the VHF power is low. This is supported by XRD measurement shown in Figure 3. The effect 2) of VHF bias becomes dominant and enhances disordering atoms/molecules of FePt in the film so to reduce in-plane coercivity when VHF power is high. The highest in-plane coercivity achieved at the composition of 16 Vol.% MgO under a proper VHF plasma irradiation during sputtering suggests the importance of both FePt atoms ordering and MgO molecules' isolation effects for making high coercivity films. This is also supported by the (FePt)\(_{65}\)(MgO)\(_{35}\) film's behavior as shown in Figure 5. It is clearer that an optimized VHF bias power (enhancement of FePt ordering) and more MgO concentration (more isolations of FePt grains) can give higher in-plane coercivity (more than 20 kOe) to FePt films.

The two kinds of MFM tips with FePt and (FePt)\(_{84}\)(MgO)\(_{16}\) coatings were fabricated for evaluation of the AC magnetic field of a write head having three surrounding shields. The (FePt)\(_{84}\)(MgO)\(_{16}\) film was formed under a VHF plasma irradiation power of 15 W. The nominal thickness of both FePt-base coatings was 40 nm. Here, we discussed the evaluation of magnetic properties of MFM tips by using pulsed magnetic field magnetic force microscope\(^{31}\), and also estimated the coercivity of MFM tips\(^{32}\). The measured coercivity of FePt-MgO MFM tips was closed to the values of FePt-MgO films. The A-MFM measurement was taken at a lift height of 8 nm. The head write current was 40 mA. Figs. 6 (a) shows the topographic image of the write head around the main pole area.

The amplitude images of AC magnetic field generated from the write head measured by the FePt-coated tip and (FePt)\(_{84}\)(MgO)\(_{16}\)-coated tip having an coercivity of 15.9 kOe is clear and has high amplitude signal at the main pole position. In contrast, the amplitude image measured
by FePt-coated tip having a coercivity of 9.2 kOe is unclear and has very low amplitude signal at the main pole position. In contrast, the amplitude image measured by FePt-coated tip having a coercivity of 9.2 kOe is unclear and has very low amplitude signal at the main pole position. These results indicate that the FePtMgO-coated tip with a coercivity higher than the field generated from the write head can effectively image the AC magnetic field without signal decay because the high coercivity can suppress the tip’s magnetization rotation. In one word, the clear amplitude image is obtained by the FePtMgO-coated tip with a high coercivity in this case.

In order to clarify and enhance the spatial resolution of our High coercivity MFM tips, a 20 nm-thick (FePt)84(MgO)16-coated tip was fabricated under the same conditions as above. Figs. 7 (a) and (b) are amplitude and phase images of the AC magnetic field for the magnetic write head measured by this tip. The lift height was fixed at 1 nm. The head write current was also 40 mA. Figs. 7 (c) and (d) are down track line profiles of amplitude and phase signal over the white line locations in Figs. 7 (a) and (b), respectively. The clear amplitude image and high amplitude signal at the main pole position are achieved again. This further indicates that the MFM tip with a coercivity higher than the AC magnetic field to be measured can effectively image the AC magnetic field without signal decay. The phase image near the main pole region was measured in the same scan. The phase difference between the bright and dark area was about 180° as shown in the line profile of Figs. 7 (d). When the direction of the perpendicular AC magnetic field is reversed from \( H_{ac} \) to \( -H_{ac} \), the input signal of a lock-in amplifier changes in the following way.

\[
-H_{ac} \cos(\omega t) = H_{ac} \cos(\omega t + \pi)
\]

Therefore, the areas with bright and dark colors in the phase image correspond to the opposite directions of perpendicular magnetic field. In another words, the phase image gives the polarity of the AC magnetic field vertical to the surface measured.

Figs. 7 (e) shows the spatial resolution of the amplitude imaging. The resolution is obtained from Fourier transformation of the amplitude scan line around main pole. The details of this calculation were described in reference papers. The spatial resolution of amplitude imaging is 15.5 nm in this case. This value is very close to the result of our previous study. Here, the coercivity of FePtMgO films maintains more than 15 kOe, even if its film thickness is reduced to 10 nm. Therefore, the FePtMgO MFM tip with the thin FePtMgO film is expected to be useful for improvement of the spatial resolution owing to the reduction of diameter of end point of the tip. In consideration of that the head structure having three surrounding shields and a high write current of 40 mA, the high coercivity FePtMgO-coated MFM tip is so successful in imaging such high magnetic field from the head.

4. Conclusion

In-plane (111)-textured FePt and FePtMgO films were deposited on pre-oxidized Si substrates and Si tips for the study of the effect of coercivity of magnetic coatings on MFM tips. The coercivity of FePtMgO coatings rises when increasing the MgO's concentration in FePtMgO alloys under an optimized VHF plasma
irradiation power. The high coercivity of FePt·MgO films is believed due to the isolation of FePt grains by MgO and enhancement of atomic ordering of FePt by a VHF bias. A clear amplitude image and high amplitude signal at the main pole position were observed by using this High coercivity FePt·MgO tip. The spatial resolution of this type of MFM tip is around 15 nm. As simply speaking, the cone-shape FePt·MgO-coated MFM tip with a coercivity higher than the magnetic field to be measured is effective and capable to measure the high AC magnetic field for a perpendicular magnetic write head at a very high write current.

Acknowledgements This work was supported by JST/SENTAN.

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Received Nov. 23, 2016: Revised Aug. 28, 2018: Accepted Nov. 05, 2018