

## Preparation of high-resolution magnetic force microscope tips coated with Co and FeCo films

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**Abstract.** Magnetic force microscope (MFM) tips are prepared by coating Si tips of 4 nm radius with Co and Fe<sub>65</sub>Co<sub>35</sub> (at. %) films by employing an ultra-high vacuum evaporation system. The effect of coating film thickness on MFM spatial resolution is investigated. With increasing the thickness from 10 to 20 nm, the resolutions of Co- and FeCo-coated tips improve from 8.4 to 6.9 nm and from 7.5 to 6.6 nm, respectively. Better resolutions are obtained for the FeCo-coated tips, which is due to enhanced sensitivities related with the higher magnetic moment of FeCo material. As the coating thickness further increases, the resolutions deteriorate due to increase of tip radius. The resolution is affected by the detection sensitivity and the tip radius. Magnetic bits of a perpendicular medium recorded at 1800 kFCI (bit length: 14.1 nm) and 1900 kFCI (13.4 nm) are respectively distinguishable in the MFM images observed by using tips coated with Co and FeCo films.

### 1 Introduction

Magnetic force microscopy (MFM) has been widely used to investigate nano-scale magnetization structures of magnetic devices like hard-disk-drive (HDD) media. MFM spatial resolution better than 10 nm is necessary to observe the magnetic bits of future HDD media with the areal densities exceeding 1 Tb/in<sup>2</sup>. MFM tip is the key element in determining the spatial resolution. MFM tips are generally prepared by coating non-magnetic sharp tips with magnetic materials. However, the resolution of commercially available MFM tip is limited at around 20 nm. Various methods, such as reducing MFM tip radius using a focused ion beam, employment of a carbon nanotube, one-side coating of non-magnetic tip with magnetic material, etc. have been tried to improve the resolution [1]–[13]. An important purpose of these studies is to reduce the volume of magnetic material at the top part of MFM tip which interacts magnetically with an observation sample. In our previous studies [14]–[18], MFM tips were prepared by coating Si tips with various magnetic materials of Fe, Co, Ni, Ni-Fe, Fe-B, Co-Cr-Pt, FePt, FePd, and CoPt. Resolutions better than 10 nm were obtained by selecting the coating material. It was also found that the resolution was influenced by not only the tip radius but also by the signal detection sensitivity which depended on coating magnetic material. Co and FeCo-alloy are typical magnetic materials with high magnetic moments and tips coated with these materials are expected to offer high detection sensitivities. In the present study, MFM tips are prepared by coating sharp Si tips with Co and FeCo-alloy films. The influence of

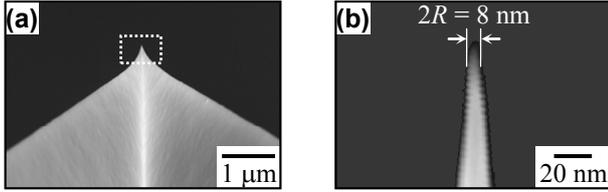
coating thickness on the MFM spatial resolution is systematically investigated.

### 2 Experimental procedure

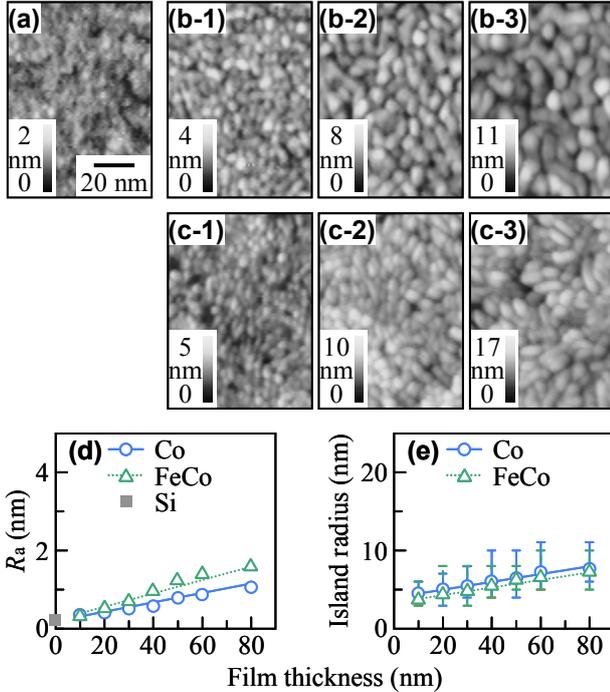
An ultra-high vacuum electron beam evaporation system was used for film coating. The base pressures were lower than  $3 \times 10^{-8}$  Pa. MFM tips were prepared by coating commercial Si tips of 4 nm radius with Co and Fe<sub>65</sub>Co<sub>35</sub> (at. %) films at room temperature by varying the thickness in a range between 10 and 80 nm. The Si tip of 4 nm radius, which is much smaller than the coating film thickness, was employed as a base-tip to reduce an influence of base-tip radius on the radius of tip after film coating. The shape of base-Si tip was observed by scanning electron microscope (SEM). Figure 1 shows the SEM images observed for a Si tip. The radius of 4 nm is confirmed. The thicknesses were estimated for films deposited on flat substrates which were placed near the base-Si tips. The deposition rate was fixed at 0.01 nm/s for both materials.

In order to investigate the structural and the magnetic properties, Co and FeCo films were also deposited on Si substrates. The film surface morphology was observed by atomic force microscopy (AFM). The magnetic properties were measured by using a vibrating sample magnetometer.

MFM observations were carried out at room temperature under pressures lower than 0.1 Pa. MFM tips were magnetized using an electromagnet along the tip



**Fig. 1.** (a) SEM image observed for a Si tip. (b) Enlarged view of the area surrounded by white square line.

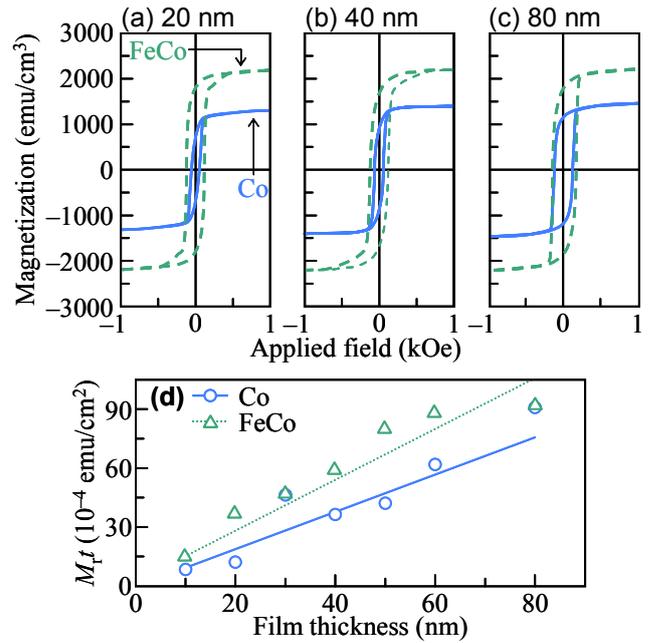


**Fig. 2.** (a)–(c) AFM images observed for (a) a Si substrate and (b) Co and (c) FeCo films formed on Si substrates. The film thicknesses are (b-1, c-1) 20, (b-2, c-2) 40, and (b-3, c-3) 80 nm. (d, e) Dependences of (d)  $R_a$  and (e) island radius of thickness.

axis so that the tip top possesses the south magnetic pole. A perpendicular medium recorded at linear densities ranging from 1500 to 2000 kilo-flux-change-per-inch (kFCI) was employed as an observation sample. The quality factor value, the distance between tip and observation sample, and the scanning speed were respectively 3000–6000 (dimensionless quantity), 5–10 nm, and 1.4  $\mu\text{m/s}$ .

### 3 Results and discussion

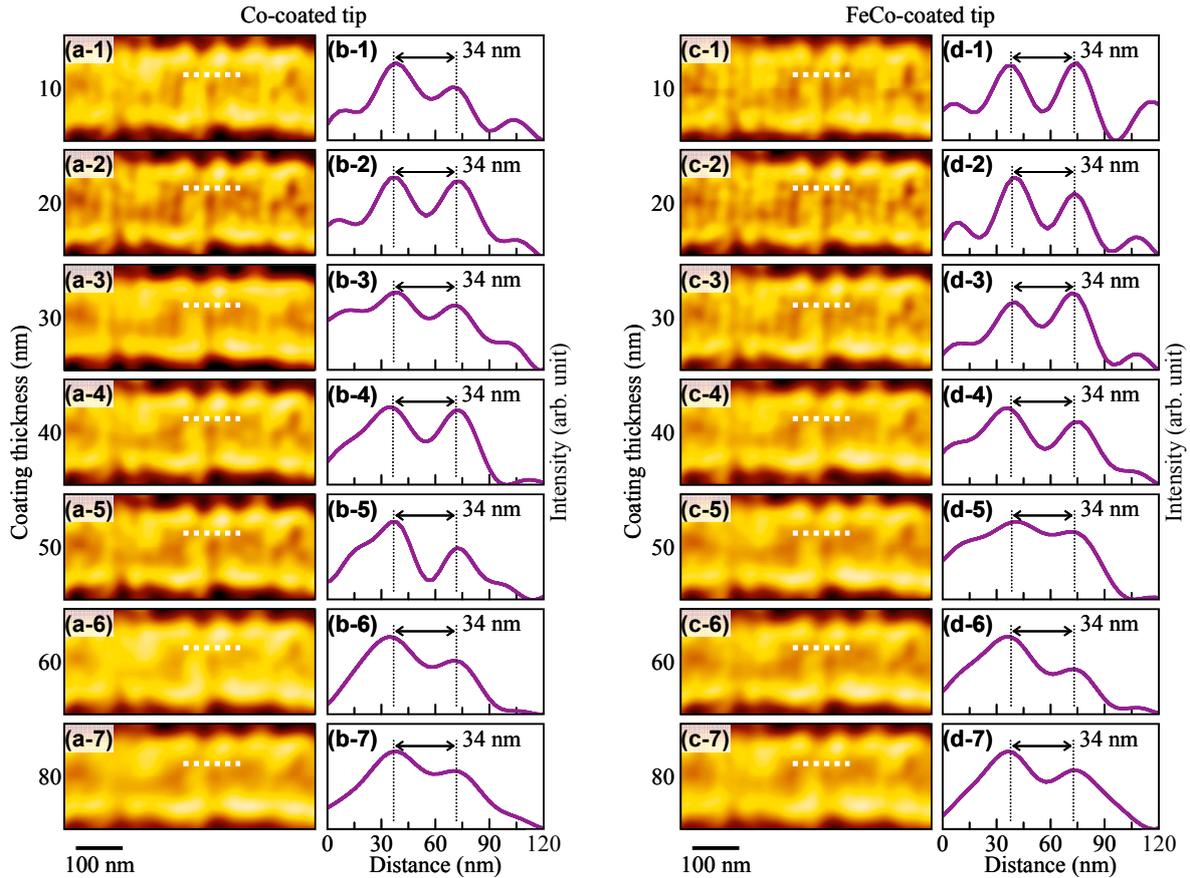
Figures 2(a)–(c) show the AFM images observed for a Si substrate and Co and FeCo films formed on Si substrates. Island-like growth is recognized for both Co and FeCo films. Figures 2(d) and (e) show the thickness dependences on arithmetical mean surface roughness ( $R_a$ ) and island radius, respectively. Here, the radius is estimated by using the relation,  $(\text{radius}) = [(\text{area}) / \pi]^{1/2}$ . With increasing the thickness, the  $R_a$  and the average island radius increase. The result indicates that not only the tip radius [14] but also the surface roughness of MFM tip increases with increasing the coating thickness.



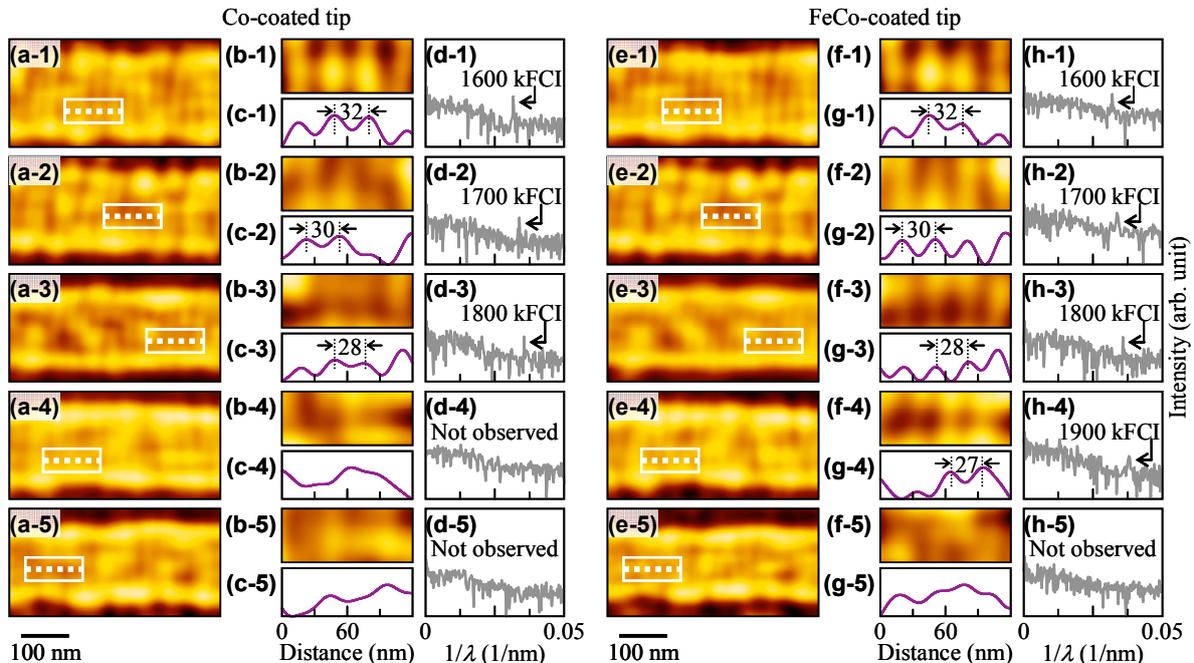
**Fig. 3.** (a)–(c) Magnetization curves measured for Co and FeCo films of (a) 20, (b) 40, and (c) 80 nm thicknesses formed on Si substrates. (d) Dependence on thickness of  $M_t$ .

Figures 3(a)–(c) show the magnetization curves of Co and FeCo films formed on Si substrates, where the magnetic field is applied in in-plane. The saturation magnetization values of Co and FeCo films are almost similar to those of bulk hcp-Co (1440  $\text{emu/cm}^3$ ) and bulk bcc- $\text{Fe}_{65}\text{Co}_{35}$  (2400  $\text{emu/cm}^3$ ) crystals, respectively. Figure 3(d) shows the dependence of film thickness on the (remanent magnetization)  $\times$  (thickness) value, that is, the remanent magnetization per unit area ( $M_t$ ). As the film thickness increases, the  $M_t$  value increases for both materials, suggesting that the signal detection sensitivity of MFM tip is improved with increasing the coating thickness. The  $M_t$  value of FeCo film is 1.5 times larger than that of Co film for a same film thickness. This result indicates that the signal detection sensitivity of FeCo-coated tip is higher than that of Co-coated tip.

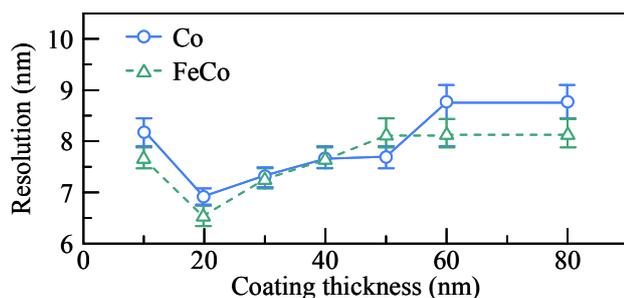
Figures 4(a) and (c) show the MFM images of a same area of perpendicular medium recorded at 1500 kFCI (bit length: 16.9 nm) observed by using MFM tips coated with Co and FeCo films with different thicknesses, respectively. Figures 4(b) and (d) show the MFM signal profiles along the dotted lines in figures 4(a) and (c), respectively. Magnetic bit images corresponding to 1500 kFCI are observed for the investigated thicknesses. Although the tip coated with 10-nm-thick film is expected to be sharper than the tip coated with 20-nm-thick film, the MFM image observed by using the tip coated with 20-nm-thick film is clearer than that observed by using the tip coated with 10-nm-thick film for both coating materials. The reason is possibly due to that the MFM signal detection sensitivity is improved with increasing the coating thickness, as expected by the magnetization curve measurements. With increasing the coating thickness beyond 20 nm, the clearness of MFM image declines due to increase of tip radius.



**Fig. 4.** (a, c) MFM images of a same area of perpendicular medium recorded at 1500 kFCI observed by using MFM tips coated with (a) Co and (c) FeCo films. (b, d) MFM signal profiles along the dotted lines in (a, c), respectively. The coating thicknesses are (a-1)–(d-1) 10, (a-2)–(d-2) 20, (a-3)–(d-3) 30, (a-4)–(d-4) 40, (a-5)–(d-5) 50, (a-6)–(d-6) 60, and (a-7)–(d-7) 80 nm.



**Fig. 5.** (a, e) MFM images of a perpendicular recording medium observed by using MFM tips coated with (a) Co and (e) FeCo films of 20 nm thickness. (b, f) Enlarged views of the areas surrounded by white square lines, (c, g) the signal profiles along the dotted lines, and (d, h) the power spectra analyzed for the magnetic bit images in (a, e), respectively. The linear recording densities are (a-1)–(h-1) 1600, (a-2)–(h-2) 1700, (a-3)–(h-3) 1800, (a-4)–(h-4) 1900, and (a-5)–(h-5) 2000 kFCI.



**Fig. 6.** Dependence on thickness of the MFM spatial resolution estimated for Co- and FeCo-coated tips.

In order to investigate the resolution, MFM observations of magnetic bits recorded at linear densities ranging from 1600 to 2000 kFCI were carried out. Figures 5(a) and (e) show the MFM images of medium recorded at densities ranging from 1600 to 2000 kFCI observed by using MFM tips coated with 20-nm-thick Co and FeCo films. Figures 5(b, f) and (c, g) show the enlarged views of the areas surrounded by white square lines and the signal profiles along the dotted lines in figures 5(a, e), respectively. Fast Fourier Transformation (FFT) was also performed for the magnetic bit images in figures 5(a, e). Figures 5(d, h) show the power spectra. Magnetic bits corresponding to 1800 and 1900 kFCI recording are respectively recognized for the Co- and the FeCo-coated tips. Thus, the MFM resolutions of Co- and FeCo-coated tips are respectively between  $14.1 / 2 = 7.1$  nm (1800 kFCI) and  $13.4 / 2 = 6.7$  nm (1900 kFCI) and between 6.7 nm (1900 kFCI) and  $12.7 / 2 = 6.4$  nm (2000 kFCI), that is,  $6.9 \pm 0.2$  nm and  $6.6 \pm 0.2$  nm. Figure 6 summarizes the resolutions of tips coated with Co and FeCo films with different thicknesses. With increasing the thickness from 10 to 20 nm, the resolutions of Co- and FeCo-coated MFM tips improve from 8.4 to 6.9 nm and from 7.5 to 6.6 nm, respectively. This is due to that the signal detection sensitivity is enhanced. With further increasing the thickness, the resolution decreases due to increase of tip radius. As a result, the tips coated with 20-nm-thick films show higher resolutions, compared with the cases of other coating thicknesses. The MFM resolution is influenced by both the detection sensitivity and the tip radius. The tip coated with 20-nm-thick FeCo film shows a very high resolution of 6.6 nm. A magnetic material with higher moment is proved to be suitable as the coating material to obtain high resolutions.

## 4 Conclusions

MFM tips are prepared by coating Si tips of 4 nm radius with Co and FeCo-alloy films. The effect of coating thickness on the MFM spatial resolution is systematically investigated. With increasing the thickness from 10 to 20 nm, the signal detection sensitivity improves and the MFM resolution increases. Resolutions of 6.9 and 6.6 nm are achieved with the tips coated with 20-nm-thick Co

and FeCo films, respectively. A material with higher magnetic moment is useful as a coating material, since the material offers a higher signal detection sensitivity. With increasing the thickness beyond 20 nm, the resolution decreases due to increase in tip radius. The MFM resolution is influenced by both the signal detection sensitivity and the tip radius. By adjusting the coating thickness, Co- and FeCo-coated MFM tips are effective to observe the magnetization structures of future HDD media.

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