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Switching fields of high-resolution magnetic force microscope tips coated with Co, $Co_{75}Pt_{10}Cr_{15}$, $Co_{75}Pt_{25}$, and $Co_{50}Pt_{50}$ films

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Abstract. Magnetic force microscope (MFM) tips are prepared by coating Si tips of 4 nm radius with Co, $Co_{75}Pt_{10}Cr_{15}$, $Co_{75}Pt_{25}$, and $Co_{50}Pt_{50}$ (at. %) films of 20 nm thickness at 300 °C. The effects of coating film material on the spatial resolution and the switching field are investigated. Higher resolutions are observed in the order of $Co_{75}Pt_{10}Cr_{15}$ < ($Co_{50}Pt_{50}$, $Co_{75}Pt_{25}$) < Co. The Co-coated tip shows the highest resolution of 7.3 nm, which seems to be depending on a high detection sensitivity related with the magnetic moment of Co material. The saturation magnetization increases in the order of $Co_{75}Pt_{10}Cr_{15}$ < $Co_{50}Pt_{50}$ < $Co_{75}Pt_{25}$ < Co. Higher switching fields are observed in the order of Co < $Co_{75}Pt_{10}Cr_{15}$ < $Co_{75}Pt_{25}$ < $Co_{50}Pt_{50}$. The $Co_{50}Pt_{50}$-coated tip shows the highest switching field of 1.675±0.025 kOe, which is due to a high coercive field of the magnetic film involving $L1_1$ ordered phase with high magnetocrystalline anisotropy energy. The coercive field is recognized in the order of Co < $Co_{75}Pt_{10}Cr_{15}$ < $Co_{75}Pt_{25}$ < $Co_{50}Pt_{50}$. A tip prepared by coating $Co_{50}Pt_{50}$ film which has high resolution and high switching field is useful for MFM observations of high-density recording media and permanent magnets.

1 Introduction

Magnetic force microscopy (MFM) has been widely used to investigate the magnetization structures of hard-disk-drive (HDD) media, permanent magnets, etc. MFM tips are generally prepared by coating non-magnetic sharp tips with magnetic films [1–4]. The tip shape and the magnetic property of coated film material influence the spatial resolution and the magnetic switching field (H_{sw}) of MFM tip. The areal density of HDD medium is approaching 1 Tb/in^2, where the bit length is becoming narrower than 30 nm, where MFM resolution around 10 nm is necessary. Furthermore, future ultra-high density recording media are considered to be prepared by employing magnetic materials with high uniaxial magnetocrystalline anisotropy energies (K_u) like $L1_0$ ordered $Fe_{50}Pt_{50}$ (at. %) alloy, etc. When a magnetic tip is exposed to a high magnetic flux emanating from observation sample, the tip magnetization may reverse. Therefore, a high H_{sw} of MFM tip is also required for observations of such future media.

High H_{sw} tips have been prepared by using $L1_0$ ordered $Co_{50}Pt_{50}$ [3], $Fe_{50}Pt_{50}$ [4], and $Fe_{50}Pd_{50}$ [5, 6] alloys as coating magnetic materials. However in order to prepare $L1_0$ ordered films with high K_u, it is necessary to employ high temperature processing around 600 °C, which causes irregular surface of coated film and decrease the MFM resolution [7]. Metastable fcc-based $L1_1$ [8–11] and hcp-based $D0_{19}$ [9, 12–14] ordered phase formation has been recognized for $Co_{50}Pt_{50}$ and $Co_{75}Pt_{25}$ films with the close-packed plane parallel to the substrate surface, respectively. The ordered phases can be prepared at a lower process temperature around 300 °C. The K_u increases up to 10^7~10^8 erg/cm^3 with increasing the order degree [9, 15]. In the present study, $Co_{50}Pt_{50}$ and $Co_{75}Pt_{25}$ alloys are employed for MFM tip preparations in addition to conventional coating materials of Co and $Co_{75}Pt_{10}Cr_{15}$ alloy. These magnetic materials are formed on Ru-coated base-Si tips. The Ru layer is introduced to make the close-packed plane of magnetic film parallel to the base-tip surface. The resolutions and the H_{sw} values are compared.

2 Experimental procedure

MFM tips were prepared by coating base-Si tips of 4 nm radius with films by employing a radio-frequency (RF) magnetron sputtering system with the base pressures lower than 4×10^{-7} Pa. Ru, Co, $Co_{75}Pt_{10}Cr_{15}$, $Co_{75}Pt_{25}$, and $Co_{50}Pt_{50}$ targets of 3 in diameter were used. The distance between target and Si tip was 150 mm. The Ar gas pressure was kept constant at 0.67 Pa. The deposition rate was 0.02 nm/s for all the materials.

An 5-nm-thick Ru layer and a 20-nm-thick Co, $Co_{75}Pt_{10}Cr_{10}$, $Co_{75}Pt_{25}$, or $Co_{50}Pt_{50}$ film were sequentially deposited on Si tip at 300 °C. The thicknesses were estimated for films deposited on flat Si substrates which were located near the Si tips. The films deposited on flat substrates were also employed for the structural and magnetic characterizations of coated film materials.

The tip shapes were observed by scanning electron microscopy (SEM). The crystal structure was

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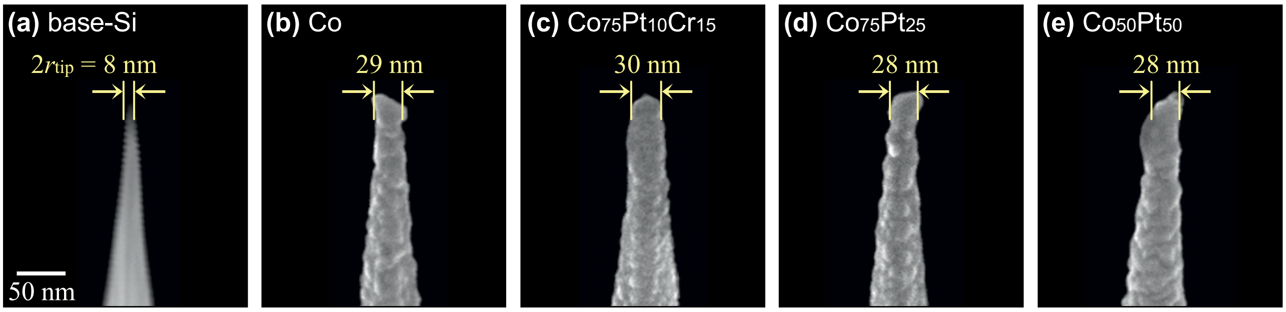

Fig. 1. SEM images observed (a) for a Si tip and (b)–(e) for MFM tips coated with (b) Co, (c) $Co_{75}Pt_{10}Cr_{15}$, (d) $Co_{75}Pt_{25}$, and (e) $Co_{50}Pt_{50}$ films.

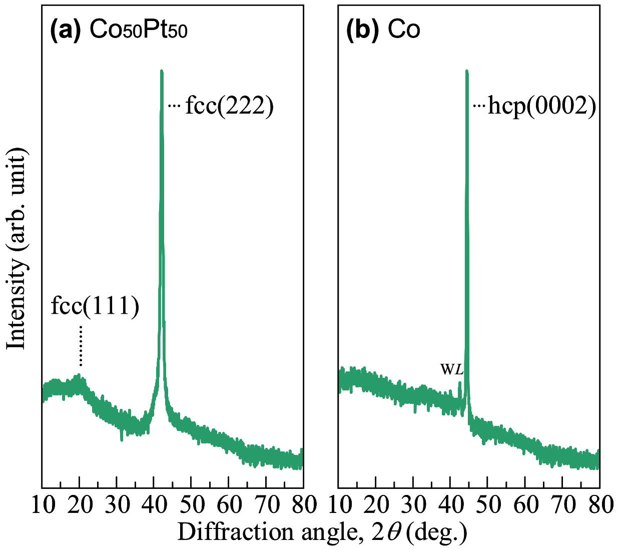

Fig. 2. XRD patterns of (a) Co and (b) $Co_{50}Pt_{50}$ films of 200 nm thickness formed on Ru/Si substrates. The intensity is shown in a logarithmic scale.

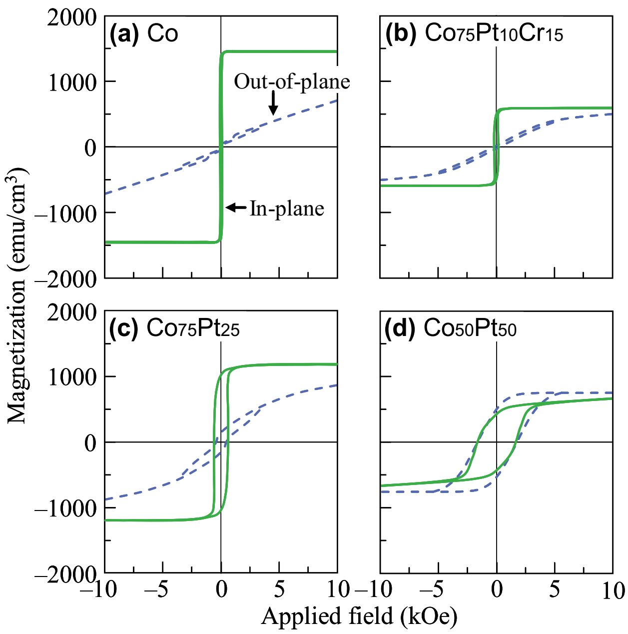

Fig. 3. Magnetization curves measured for (a) Co, (b) $Co_{75}Pt_{10}Cr_{15}$, (c) $Co_{75}Pt_{25}$, and (d) $Co_{50}Pt_{50}$ films of 20 nm thickness formed on Ru/Si substrates.

investigated by θ-2θ scan X-ray diffraction (XRD) with Cu-Kα radiation (wave length = 0.15418 nm). The magnetic properties were measured by using a vibrating sample magnetometer (VSM). MFM tips were magnetized along the tip axis by applying a magnetic field of 10 kOe so that the tip top possessed the south magnetic pole.

MFM observations were carried out at room temperature under pressures lower than 0.1 Pa by using a scanning probe microscope unit, SPI4000/SPA-300HV (SII Nano Technology Inc.). A perpendicular medium recorded at linear densities ranging from 500 to 1800 kilo-flux-change-per-inch (kFCI) and a commercial HDD perpendicular medium with the areal density of 163 Gb/in^2 were used as observation samples. The quality factor value, the distance between tip (the lowest point of cantilever oscillation) and observation sample, and the scanning speed were 2900~4200 (dimensionless quantity), 4 ± 1 nm, and 1.4 μm/s, respectively. The resolution and the H_{sw} of MFM tip were carefully determined by optimizing the observation condition.

3 Results and discussion

Figure 1(a) shows the SEM image observed for a base-Si tip. The radius of 4 nm is confirmed. Figures 1(b)–(e) show the SEM images observed for MFM tips prepared by coating Co, $Co_{75}Pt_{10}Cr_{15}$, $Co_{75}Pt_{25}$, and $Co_{50}Pt_{50}$ films on Ru-coated Si tips. The radiuses of tips are constant at around 28 nm for all the materials.

Figure 2(a) shows the XRD pattern of $Co_{50}Pt_{50}$(200 nm)/Ru(5 nm) film formed on flat Si substrate. The thick film sample was employed to increase the XRD detection sensitivity. Superlattice fcc(111) reflection is clearly recognized around 2θ = 21° in addition to fundamental fcc(222) reflection. The result shows that the film involves fcc-based $L1_1$ ordered phase. The long-range order degree is estimated from the XRD data to be 0.13. The calculation method is reported in our previous paper [11]. The reflection from Ru layer is absent due to that the thickness of Ru layer is as thin as 5 nm. Figure 2(b) shows the XRD pattern of Co(200 nm)/Ru(5 nm) film Only the hcp(0002) reflection is observed. Similar XRD patterns were recognized for the $Co_{75}Pt_{10}Cr_{10}$ and the $Co_{75}Pt_{25}$ films formed on Ru/Si substrates (not shown here). There is a possibility that the $Co_{75}Pt_{25}$ film may include hcp-based $D0_{19}$ ordered phase, since the hcp(0001) reflection which is considered to appear around 21° is forbidden in the case of $D0_{19}$ structure [11].

Figure 3 shows the magnetization curves of Co, $Co_{75}Pt_{10}Cr_{15}$, $Co_{75}Pt_{25}$, and $Co_{50}Pt_{50}$ films of 20 nm thickness formed on Ru/Si substrates. Higher saturation magnetization values are observed in the order of

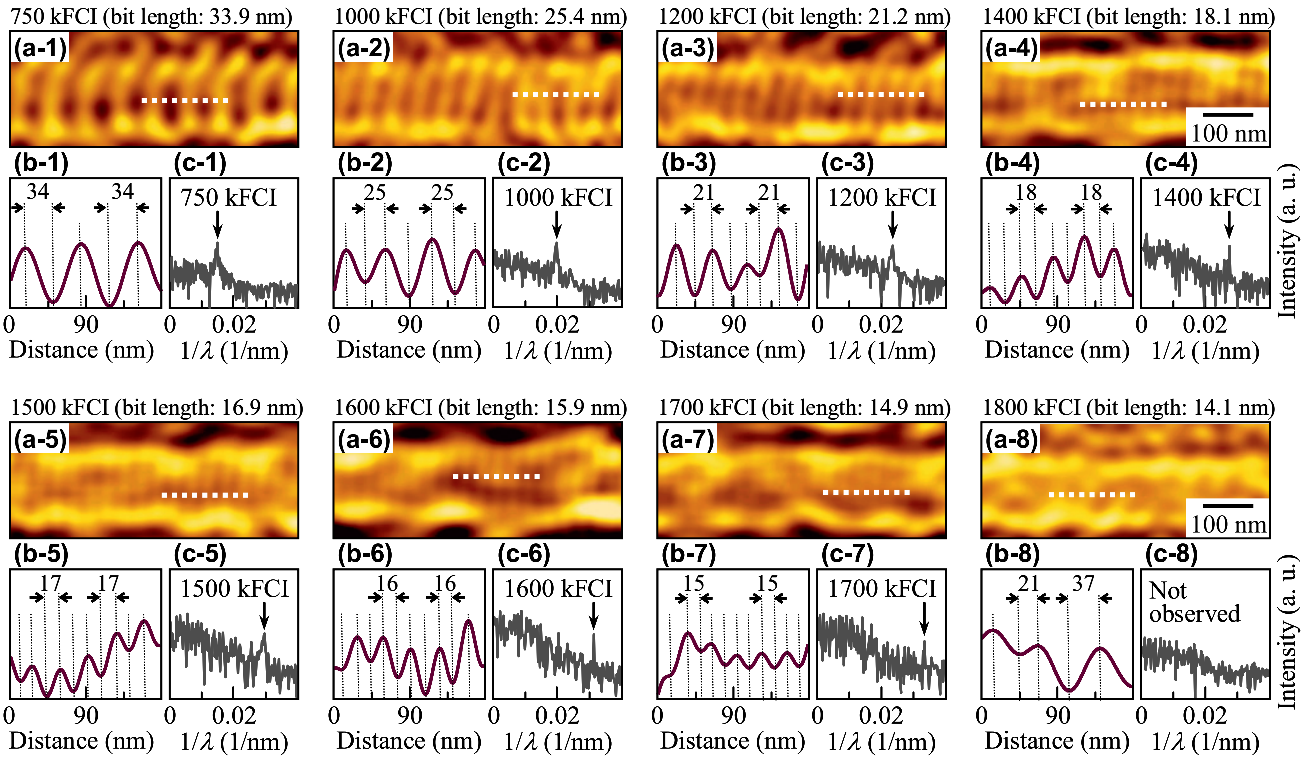

Fig. 4. (a) MFM images of a perpendicular medium recorded at (a-1) 750, (a-2) 1000, (a-3) 1200, (a-4) 1400, (a-5) 1500, (a-6) 1600, (a-7) 1700 and (a-8) 1800 kFCI observed by using a Co-coated tip. (b-1)–(b-8) Signal profiles along the dotted lines in (a-1)–(a-8), respectively. (c-1)–(c-8) Power spectra analyzed for the magnetic bit images of (a-1)–(a-8), respectively.

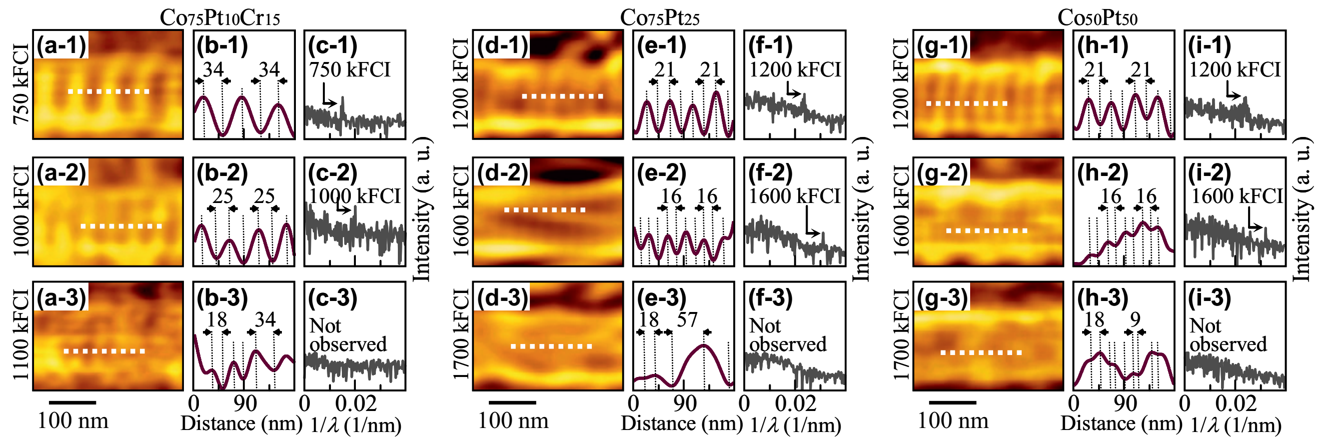

Fig. 5. (a, d, g) MFM images of a perpendicular medium recorded at (a-1) 750, (a-2) 1000, (a-3) 1100, (d-1, g-1) 1200, (d-2, g-2) 1600, and (d-3, g-3) 1700 kFCI observed by using (a) a $Co_{75}Pt_{10}Cr_{15}$-coated tip, (d) a $Co_{75}Pt_{25}$-coated tip, and (g) a $Co_{50}Pt_{50}$-coated tip. (b, e, h) Signal profiles along the dotted lines in (a, d, g), respectively. (c, f, i) Power spectra analyzed for the magnetic bit images of (a, d, g), respectively.

$Co_{75}Pt_{10}Cr_{15}$ < $Co_{50}Pt_{50}$ < $Co_{75}Pt_{25}$ < Co. The result indicates that the detection sensitivity of MFM tip increases for the coating material in the order of $Co_{75}Pt_{10}Cr_{15}$ < $Co_{50}Pt_{50}$ < $Co_{75}Pt_{25}$ < Co. Higher coercive fields (H_c) are recognized in the order of Co < $Co_{75}Pt_{10}Cr_{15}$ < $Co_{75}Pt_{25}$ < $Co_{50}Pt_{50}$, suggesting that the H_{sw} of tip is higher for the coating material; Co < $Co_{75}Pt_{10}Cr_{15}$ < $Co_{75}Pt_{25}$ < $Co_{50}Pt_{50}$. High H_c values of $Co_{50}Pt_{50}$ and $Co_{75}Pt_{25}$ films seem to be related with the magnetic properties of high K_u ordered phases included in the films.

In order to determine the resolutions of MFM tips, MFM observations were carried out for a perpendicular medium recorded at linear densities ranging from 500 to 1800 kFCI. Figure 4(a) is the MFM images observed by using a Co-coated tip. Sharpness of MFM image degrades with increasing the linear density. Figure 4(b) shows the signal profiles measured along the dotted lines in figure 4(a). Fast Fourier transformation was also performed for the magnetic bit images of figure 4(a). Figure 4(c) shows the power spectra. Magnetic bits and signal peaks corresponding to densities ranging from 750 kFCI (bit length: 33.9 nm) to 1700 kFCI (bit length: 14.9 nm) are recognized as shown in figures 5(b) and (c), respectively. However, bits of 1800 kFCI (bit length: 14.1 nm) are not distinguishable. MFM resolution is thus between 14.9/2 = 7.5 nm (1700 kFCI) and 14.1/2 = 7.1 nm (1800 kFCI), that is, 7.3±0.2 nm. Figure 5 shows the

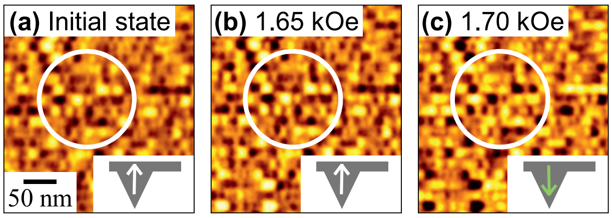

Fig. 6. MFM images of a same area of HDD perpendicular medium observed by using an MFM tip coated with $Co_{50}Pt_{50}$ film (a) before and (b, c) after applying magnetic fields of (b) 1.65 and (c) 1.70 kOe. The contrast is reversed for (c).

results of MFM observations carried out by employing $Co_{75}Pt_{10}Cr_{15}$-, $Co_{75}Pt_{25}$-, and $Co_{50}Pt_{50}$-coated tips, respectively. Magnetic bits corresponding to 1000, 1600, and 1600 kFCI recording are respectively recognized for the $Co_{75}Pt_{10}Cr_{15}$-, $Co_{75}Pt_{25}$-, and $Co_{50}Pt_{50}$-coated tips. Thus, the MFM resolutions of $Co_{75}Pt_{10}Cr_{15}$-, $Co_{75}Pt_{25}$-, and $Co_{50}Pt_{50}$-coated tips are 12.7/2~11.6/2 (12.1±0.6), 15.9/2~14.9/2 (7.7±0.2), and 15.9/2~14.9/2 (7.7±0.2), respectively. Higher resolutions are observed in the order of $Co_{75}Pt_{10}Cr_{15}$ < ($Co_{50}Pt_{50}$, $Co_{75}Pt_{25}$) < Co. The result is apparently reflecting the detection sensitivity of MFM tip related with the magnetic moment of coated film material which is expected from the VSM data.

In order to investigate the magnetic switching field, H_{sw}, MFM observations were repeated for an MFM tip before and after applying a magnetic field using the HDD medium (163 Gb/in^2) sample. The applied field direction was opposite to the initial magnetization direction of MFM tip. The magnetic field was increased in a step-wise of 0.05 kOe. The H_{sw} was estimated as the magnetic field where the contrast of MFM image was reversed. Figure 6 shows the MFM images of a same area of HDD medium observed by using a $Co_{50}Pt_{50}$-coated tip before and after applying magnetic fields. When a field of 1.65 kOe is applied to the tip [figure 6(b)], the MFM contrast does not change when compared with the initial magnetization state shown in figure 6(a). With increasing the field up to 1.70 kOe, the contrast is reversed as shown in figure 6(c). Thus, the H_{sw} is between 1.65 and 1.70 kOe, that is, 1.675±0.025 kOe. Similar measurements were performed for Co-, $Co_{75}Pt_{10}Cr_{15}$-, and $Co_{75}Pt_{25}$-coated tips. The H_{sw} of Co-, $Co_{75}Pt_{10}Cr_{15}$-, and $Co_{75}Pt_{25}$-coated tips are respectively determined to be 0.375±0.025, 0.475±0.025, and 1.075±0.025 kOe. A higher H_{sw} is observed in the order of Co- < $Co_{75}Pt_{10}Cr_{15}$- < $Co_{75}Pt_{25}$- < $Co_{50}Pt_{50}$-coated tips, which is related with the H_c shown in figure 3. The H_{sw} of all MFM tips are larger than the H_c of those magnetic films deposited on flat Si substrate. The enhancement is possibly due to an influence of shape magnetic anisotropy. The highest H_{sw} is obtained for the $Co_{50}Pt_{50}$-coated tip, which is possibly due to a high magnetic anisotropy of the $Co_{50}Pt_{50}$ film related with an inclusion of $L1_1$ ordered phase. The present study apparently shows that a high resolution MFM tip with high H_{sw} is realizable by using the ordered $Co_{50}Pt_{50}$-alloy as a coating material.

4 Conclusion

MFM tips are prepared by coating Si tips with Co, $Co_{75}Pt_{10}Cr_{15}$, $Co_{75}Pt_{25}$, and $Co_{50}Pt_{50}$ films of 20 nm thickness at 300 °C. The influences of coating material on the spatial resolution and the H_{sw} are investigated. Resolutions of 7.3±0.2, 12.1±0.6, 7.7±0.2, and 7.7±0.2 nm are achieved with the Co-, $Co_{75}Pt_{10}Cr_{15}$-, $Co_{75}Pt_{25}$-, and $Co_{50}Pt_{50}$-coated tips, respectively. A material with higher magnetic moment is useful as a coating material, since the material offers a higher signal detection sensitivity. Switching fields of 0.375±0.025, 0.475±0.025, 1.075±0.025, and 1.675±0.025 kOe are obtained with the Co-, $Co_{75}Pt_{10}Cr_{15}$-, $Co_{75}Pt_{25}$-, and $Co_{50}Pt_{50}$-coated tips, respectively. A $Co_{50}Pt_{50}$-coated MFM tip is useful to observe the magnetic domain structures of future high density and high K_u HDD media and permanent magnets.

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