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The Magnetic Properties of Co-Ni-Fe-N Soft Magnetic Thin Films

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Co-Ni-Fe-N thin films were fabricated by a N_2 reactive rf magnetron sputtering method. The nitrogen partial pressure (P_{N2}) was varied in the range 0~10%. As P_{N2} increases in this range, the saturation magnetization (B_s) linearly decreases from 19.8 kG to 14 kG and the electrical resistivity (ρ) increases from 27 to 155 $\mu\Omega$cm. The coercivity (H_c) exhibits the minimum value at 4% P_{N2}. The magnetic anisotropy fields (H_k) are in the range of 20~50 Oe. High frequency characteristics of $(Co_{22.2}Ni_{27.6}Fe_{50.2})_{100-x}N_x$ films are excellent in the range of 3~5% of P_{N2}. In particular, the effective permeability of the film fabricated at 4% P_{N2} is 800, which is maintained up to 600 MHz. This film also shows Bs of 17.5 kG, H_c of 1.4 Oe, resistivity of 98 $\mu\Omega$cm and H_k of about 25 Oe. Also, the corrosion resistance of $(Co_{22.2}Ni_{27.6}Fe_{50.2})_{100-x}N_x$ films was improved with increasing N concentration.

1. Introduction

Recent developments in electronic devices have led to a demand for further miniaturization and higher frequency (f > 100 MHz) operation in magnetic devices such as magnetic heads and magnetic sensors. One of the important properties of magnetic materials for such applications is high permeability (μ) at high frequency, which is limited by eddy current loss and ferromagnetic resonance. To improve high frequency characteristics of soft magnetic films, the films must have not only high electrical resistivity but also high saturation magnetization and magnetic anisotropy [1]. We recently have reported as-deposited Co-Ni-Fe soft magnetic thin films which have Bs of about 20 kG, H_c of 1.5~2.5 Oe and an effective permeability of about 1100 up to 100 MHz [2]. However, the high frequency properties rapidly deteriorate above 100 MHz due to the low electrical resistivity and relatively small anisotropy field of these films.

In this study we have investigated the effects of N_2 addition on the high frequency characteristics of Co-Ni-Fe soft magnetic films, by magnetic measurements and structural analysis.

2. Experimental

As-deposited Co-Ni-Fe-N thin films were fabricated by rf magnetron sputtering using a composite target. The sputtering chamber was first pumped down to $\sim 1 \times 10^{-6}$ Torr. The deposition was then carried out under an $(Ar + N_2)$ atmosphere with a total gas pressure of 1×10^{-3} Torr. The input power was fixed at 450W, and the nitrogen partial pressure (P_{N2}) varied in the range 0~10% of the total pressure. The thickness of the Co-Ni-Fe-N thin films was measured at about 500 nm. The structures of the films were analyzed by X-ray diffraction (XRD) and transmission electron microscopy (TEM), and the composition analyzed by electron probe microanalysis (EPMA). B_s, H_c, and H_k were measured using a vibrating sample magnetometer (VSM). The permeability was measured using a PMF-001 permeability measurement system. This device is a high frequency permeability measurement system in the frequency range from 1.0 to 700 MHz using a network analyzer and s-parameter. The electrical resistivity was measured by a four-point probe method. The corrosion resistance of Co-Ni-Fe-N thin films was evaluates using an EG & G PAR 273A electrochemical test system. Table 1 shows the sputtering condition of Co-Ni-Fe-N thin films.

Table 1. The sputtering condition of CoNiFeN thin films

Target	Composite Target Fe disc + (Co, Ni) chips
Substrate/Condition	Si (100)/Water cooling
Vacuum	$< 1 \times 10^{-6}$ Torr
Target Substrate Distance	6.5 cm
RF Input Power	450 W
Total Pressure $(Ar + N_2)$	1 mTorr
Nitrogen Partial Pressure (P_{N2})	0~10%
Film Thickness	500 ± 100 nm

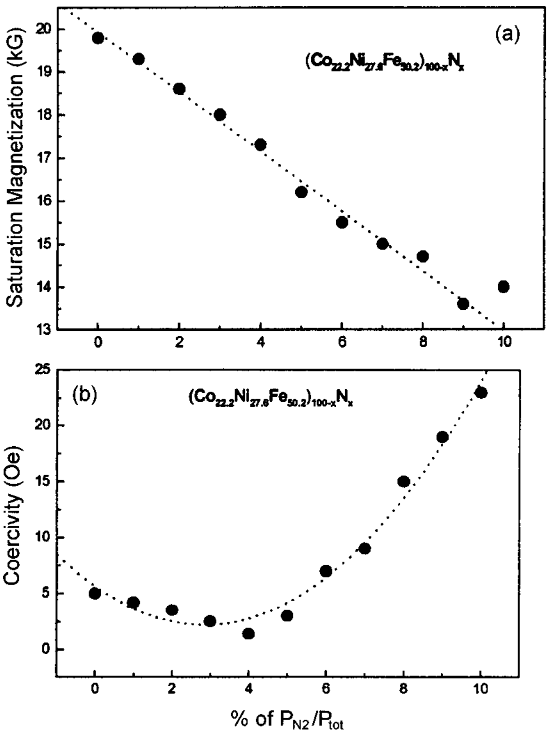

Fig. 1. Saturation magnetization (a) and Coercivity (b) for $(Co_{22.2}Ni_{27.6}Fe_{50.2})_{100-x}N_x$ films.

3. Results and Discussion

As P_{N2} increases from 0% to 10%, the B_s of $(Co_{22.2}Ni_{27.6}Fe_{50.2})_{100-x}N_x$ (x = 0~8.7) thin films decreases continuously from 19.8 kG to 14 kG, as shown in Fig. 1(a). The H_c of these films initially decreases with the increase of P_{N2}, exhibits a minimum value at 4% P_{N2}, and increases at P_{N2} higher than 5%, as shown in Fig. 1(b).

The desirable high frequency characteristics for soft magnetic thin films are high permeability and low power loss. One of the sources of loss in ferromagnetic materials operated at high frequency is the eddy current loss. The eddy current loss increases in proportion to the square of the frequency, which means that it plays an important role at high frequency. This eddy current effect can be minimized by an increase of the skin depth which is controlled by the electrical resistance, in magnetic materials [3].

Typical easy and hard axis M-H loops of the $(Co_{22.2}Ni_{27.6}Fe_{50.2})_{96.8}N_{3.2}$ thin film deposited at 4% P_{N2} are shown in Fig. 2. The film is magnetically soft, with Hc of 1.4 Oe. From the hard axis M-H loop, H_k is estimated to be about 25 Oe. From the M-H loops, values of H_k of CoNiFeN thin films with different N concentration are measured in the range of 20~50 Oe. These values are larger than those of Co-Ni-Fe thin films, previously published elsewhere [2].

As shown in Fig. 3, the electrical resistivity of $(Co_{22.2}Ni_{27.6}Fe_{50.2})_{100-x}N_x$ films increases from 27 to 155 $\mu\Omega \cdot cm$ with increasing P_{N2}. These values are about 6 times larger than those of Co-Ni-Fe thin films. It indicates that the addition of nitrogen increases the resistivity of Co-Ni-Fe thin films significantly. Films fabricated in the range of 3~5% P_{N2} show excellent high frequency characteristics, especially at 4% P_{N2}. Even though the electrical resistivity continues to increase above 5% P_{N2}, the soft magnetic pro-

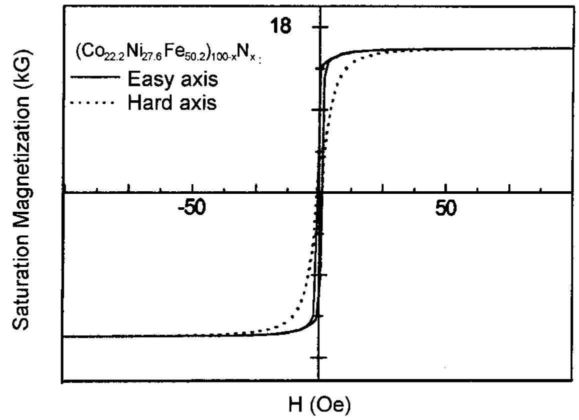

Fig. 2. Easy axis and hard axis M-H loops for $(Co_{22.2}Ni_{27.6}Fe_{50.2})_{96.8}N_{3.2}$ thin film deposited at 4% P_{N2}.

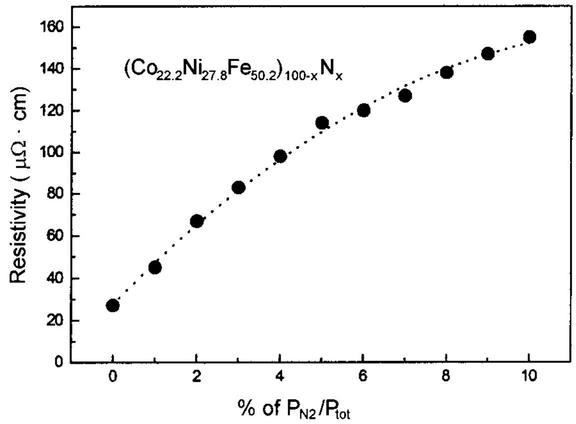

Fig. 3. Electrical resistivity of $(Co_{22.2}Ni_{27.6}Fe_{50.2})_{100-x}N_x$ thin films with the variation of P_{N2}.

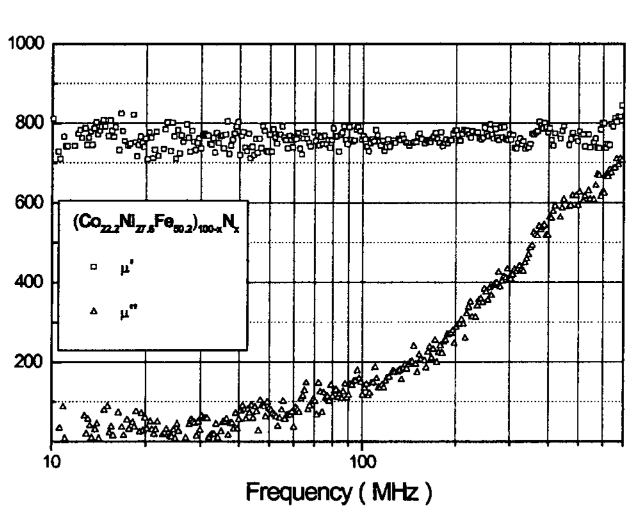

Fig. 4. Frequency dependency of effective permeability for $(Co_{22.2}Ni_{27.6}Fe_{50.2})_{96.8}N_{3.2}$ films deposited at 4% P_{N2}.

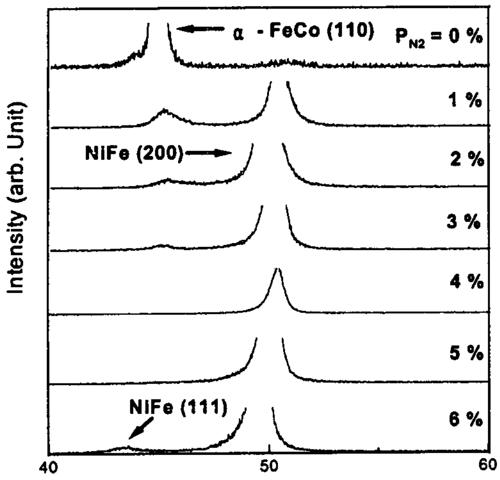

Fig. 5. Variation of XRD patterns with increasing P_{N2} for $(Co_{22.2}Ni_{27.6}Fe_{50.2})_{100-x}N_x$ films.

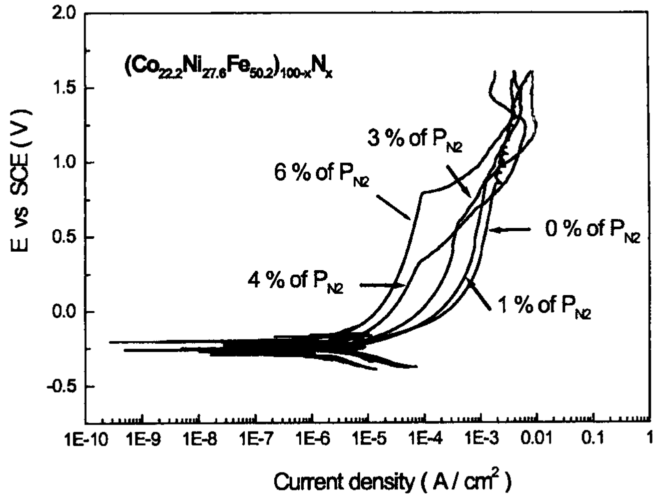

Fig. 6. Comparison of the anodic polarization curves of $(Co_{22.2}Ni_{27.6}Fe_{50.2})_{100-x}N_x$ films in 0.5 M NaCl at pH=6.

perties start to deteriorate, which results in the loss of excellent high frequency characteristics of these films. The high frequency properties of these films rapidly deteriorate above 100 MHz. Fig. 4 shows the frequency dependency of effective permeability for $(Co_{22.2}Ni_{27.6}Fe_{50.2})_{96.8}N_{3.2}$ films deposited at 4% P_{N2}. Here the effective permeability is 800, and this value is maintained up to 600 MHz. This film also has Bs of 17.5 kG, H_c of 1.4 Oe, resistivity of 98 $\mu\Omega \cdot$ cm, and H_k of about 25 Oe.

In order to understand the changes of magnetic properties in these films, XRD was used to investigate the microstructures of the films. Fig. 5 shows the XRD patterns of the Co-Ni-Fe-N thin films at various values of P_{N2}. The grain size of the films calculated by Scherrers equation is estimated to be around 10~40 nm. As P_{N2} increases to 4%, the intensity of the α-FeCo (110) peaks decreases but that of NiFe (200) peaks increases. At 4% P_{N2}, only a single NiFe(200) peak was observed. As P_{N2} increases above 5%, a NiFe (111) peak as well as a NiFe(200) peak appear. These results confirm that the increment of P_{N2} results in the increase of the NiFe phase instead of the α-FeCo(110) phase, which contributes to the improvement of soft magnetic properties. Also, the appearance of a NiFe (111) peak above 5% P_{N2} indicates (111) texture formation, which results in deterioration of soft magnetic properties [4].

To ensure reliability in magnetic devices using thin films, the film materials must possess good corrosion resistance. Therefore, we investigated the corrosion resistance of these Co-Ni-Fe-N thin films. Electrochemical corrosion data were obtained using an EG & G PAR 273A electrochemical test system and 352 Softcorr corrosion software. Potentiodynamic and cyclic polarization techniques were used to evaluate the localized corrosion resistance of the films with a passive oxide layer. The measurements were carried out at room temperature in an EG & G flat cell, where a circular area of 0.283 cm^2 of the film was exposed to air-saturated 0.5 M NaCl electrolyte at pH = 6 ± 0.1. Saturated Calomel Electrode (SCE) and 2.54 cm × 1.27 cm platinum net were used as a reference electrode and a counter electrode, respectively. The scan rate was 5 mV/sec below the corrosion potential (E_{corr}). The testing condition emulates an extreme environment to which thin film heads are exposed during packaging, storage and subsequent applications.

Fig. 6 shows the anodic polarization curves for $(Co_{22.2}Ni_{27.6}Fe_{50.2})_{100-x}N_x$ thin films with increasing ratio (%) of P_{N2}. The passivity currents are as low as 10^{-4} A/cm^2 in the potential range of ~0.75 V. From this result, the corrosion resistance of $(Co_{22.2}Ni_{27.6}Fe_{50.2})_{100-x}N_x$ thin films improves with increasing in N concentration [5, 6]. Therefore, Co-Ni-Fe-N thin films show better corrosion resistance than Co-Ni-Fe thin films.

4. Conclusions

To improve the high frequency characteristics of Co-Ni-Fe thin films, we incorporated nitrogen into the Co-Ni-Fe alloy films. We investigated the magnetic properties and corrosion resistance of Co-Ni-Fe-N thin films. The electrical resistivity and the anisotropy of Co-Ni-Fe-N films increased significantly. The Co-Ni-Fe-N thin films deposited at 4% P_{N2} have 17.5 kG Bs, 1.4 Oe H_c, 98 $\mu\Omega \cdot$ cm electrical resistivity, and about 25 Oe H_k. This film has excellent frequency characteristics, with effective permeability of about 800 maintained up to 600 MHz. The corrosion resistance of Co-Ni-Fe-N thin films improves with increasing N concentration. From these results, we confirm that Co-Ni-Fe-N thin films are good candidates for writing head materials and high frequency devices.

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