High Frequency Characteristics of Nanocrystalline Co-Fe-Hf-O Soft Magnetic Films

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Abstract. The microstructure, electrical resistivity, and high frequency soft magnetic properties of nanocrystalline Co-Fe-Hf-O films were investigated. The films were prepared by rf reactive sputtering technique in Ar + O_2 mixed atmosphere under a static magnetic field or no field. In an as-deposited state, a $Co_{44.3}Fe_{19.1}Hf_{14.5}O_{22.1}$ film deposited in a static field consists of mixed structure of amorphous phase and bcc nanocrystals with 3 - 4 nm in diameter. The real part (μ') of complex permeability of 160 is almost constant up to 1GHz, and extremely high μ'/μ'' of 61 at 100 MHz is obtained. These high frequency characteristics are caused by the high electrical resistivity (ρ) of 13 $\mu\Omega$m and large anisotropy field (H_k) of 4.8 kA/m.

1. INTRODUCTION

Recently, the soft magnetic films with low losses as at high frequency have been strongly required for the improvement and miniaturization of magnetic devices such as inductors and transformers. In high frequency region, low resistivity ρ of metallic alloy films generally result in an increase of an eddy current loss. We have been studying the high resistive Fe-M-O films (M= Hf, Zr, Y,or Rare-Earth elements) [1 - 3] , whose structure is composed of nanocrystalline bcc phase ($\leqq$ 10nm) and amorphous phase containing larger amounts of M and O elements than those of bcc phase. These films have several times higher ρ values than conventional metallic alloy films. As a result, the μ' of 1000 is constant up to 100 MHz along the magnetic hard axis. However, large H_k is also required besides the high ρ values to further reduce the loss factor in the high frequency range over 100 MHz.

In this study, we tried to induce a large H_k and to improve the high frequency characteristics by substituting Co for the major part of Fe of Fe-Hf-O films.

2. EXPERIMENTAL PROCEDURE

The films with approx. 2 μm in thickness were prepared by rf reactive sputtering technique in a mixed atmosphere of Ar and O_2 under a static magnetic field. Microstructure of the films were analyzed by a field-emission-type 200kV transmission electron microscope (TEM) with nano-beam electron diffraction and energy dispersive X-ray spectroscopy (EDX). The angular dispersion of uniaxial magnetic anisotropy (α_{90}) was measured using a B-H loop tracer [4]. Frequency dependence of μ' and μ" was measured up to 1 GHz by a parallel line technique [5].

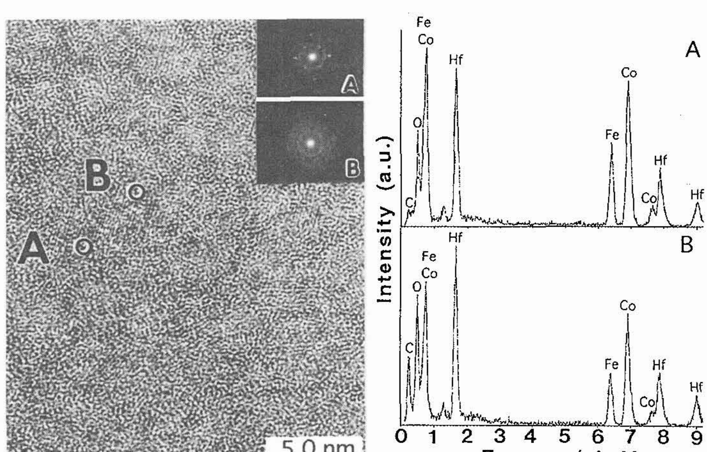

Figure 1 : High - resolution TEM image, electron diffraction patterns, and EDX spectra for an as-deposited $Co_{44.3}Fe_{19.1}Hf_{14.5}O_{22.1}$ film.

3. RESULTS AND DISCUSSION

Figure 1 shows the TEM image, electron diffraction patterns, and EDX spectra of an as-deposited $Co_{44.3}Fe_{19.1}Hf_{14.5}O_{22.1}$ film. The electron diffraction patterns and the EDX spectra were taken from the region in the TEM image indicated by A and B. The region A and B correspond to the crystalline phase and amorphous phase, respectively. The film is composed of crystalline phase below 4 nm in diameter, which is smaller than that of Fe-Hf-O films [1], and an amorphous phase surrounding them. This crystalline phase is identified as bcc phase from the electron diffraction pattern A. As can be seen in the EDX spectra, the peaks of Hf and O elements from the amorphous phase are stronger than those of the bcc phase. This means the amorphous phase contains larger amount of Hf and O elements. In addition, considerable amounts of Hf and O are supersaturated in the bcc phase.

Figure 2 shows the magnetization curves along the easy and hard axis for as-deposited $Co_{44.3}Fe_{19.1}Hf_{14.5}O_{22.1}$ film compared with those of an $Fe_{61}Hf_{13}O_{26}$ film. The magnetization curves for the magnetic easy and hard axis are indicated by ∥ and ⊥, respectively. The data of α_{90} are also shown in the figure. The $Co_{44.3}Fe_{19.1}Hf_{14.5}O_{22.1}$ film was deposited in a uniaxial field, and the $Fe_{61}Hf_{13}O_{26}$ film was annealed at 673 K for 10.8 ks under a uniaxial field of 160 kA/m after deposition with no field. The saturation magnetization (I_s) of 1.1 T and the high ρ value of 13 $\mu\Omega$ m are simultaneously obtained for $Co_{44.3}Fe_{19.1}Hf_{14.5}O_{22.1}$ film. By substituting Co for the major part of Fe, a much larger H_k of 4.8 kA/m than that of the $Fe_{61}Hf_{13}O_{26}$ film is also obtained. Consequently, the α_{90} becomes smaller than that of an $Fe_{61}Hf_{13}O_{26}$ film. The relatively small H_c of 440 A/m despite the major constituent is Co which has a large magnetocrystalline anisotropy, is attributed to the effect of very small grain size [6] below 4 nm as shown in Fig. 1. Accordingly, the frequency characteristics of this film is expected to be improved.

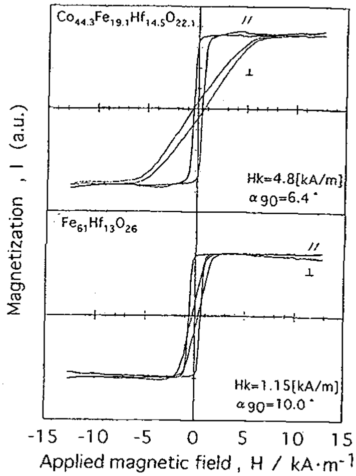

Figure 2 : Magnetization curves for an as-deposited $Co_{44.3}Fe_{19.1}Hf_{14.5}O_{22.1}$ film, and an $Fe_{61}Hf_{13}O_{26}$ film annealed at 673 K for 10.8 ks under a uniaxial magnetic field of 160 kA/m.

Figure 3 shows the frequency dependence of μ' and μ'' together with the calculated data (solid line), considering both eddy current loss and the resonance loss [7], for as-deposited $Co_{44.3}Fe_{19.1}Hf_{14.5}O_{22.1}$ film. For the calculation, the experimental data such as I_s, H_k, ρ and the film thickness are used as the parameter. The damping constant α was replaced by the data of Co based amorphous alloy film [7]. The μ' of 160 is almost flat up to 1 GHz and the μ'' is reduced drastically. As a result, the μ'/μ'' exhibits extremely high value of 61 at 100 MHz. There are some difference between the experimental and the calculated data, however, they show better agreement near 1GHz than those of the other soft magnetic films. These high frequency soft magnetic characteristics are resulted from the large H_k with a small dispersion of uniaxial magnetic anisotropy, shown in Fig. 2, and high ρ value of 13 $\mu\Omega$m. Therefore, this film has high potential for high frequency applications, such as micro magnetic devices, owing to the magnetically low loss properties in the high frequency region.

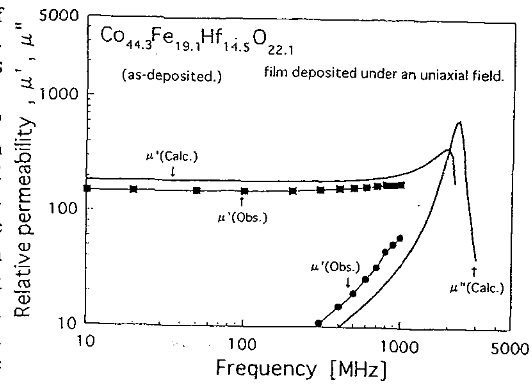

Figure 3 : Measured and calculated frequency dependence of μ' and μ'' for an as-deposited $Co_{44.3}Fe_{19.1}Hf_{14.5}O_{22.1}$ film.

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