Fabrication and Magnetic Properties of FeCoB–O Soft Magnetic Thin Films

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Keywords: Reactive magnetron sputtering, nano-granular film, high frequency characteristics

Abstract. Thin films of FeCoB-O were deposited by reactive magnetron sputtering in a Ar + O_2 atmosphere with the oxygen partial pressure R_{O2} varied. The dependence of soft magnetic properties and high frequency characteristics on oxygen partial pressure were investigated systematically. With the increase in R_{O2} from 1.1% to 1.5%, the films exhibited small coercivity H_c and large in-plane uniaxial anisotropy field H_k. A largest H_k value of 70 Oe was obtained for the sample of R_{O2} = 1.3% with H_c = 7.1 Oe, a saturation magnetization $4\pi M_s$ = 10.2 kG and a resistivity ρ = 3638 μΩ·cm were consistently obtained, resulting in excellent high frequency characteristics, such as high ferromagnetic resonance frequency of 3.0 GHz combined with a large real part of complex permeability of 145, implying that the film is promising for high frequency applications. Such good soft magnetic properties are ascribed to the exchange coupling among magnetic particles.

Introduction

With the ever-increasing of operational frequency and further demands for miniaturization in electromagnetic devices, such as micro-inductors, micro-transformers and electromagnetic noise suppressors [1-6], soft magnetic thin films with large saturation magnetization $4\pi M_s$, an appropriate large anisotropy field H_k, high resistivity ρ, and excellent high-frequency characteristics are in high demand. Metal-insulator granular films (MIGFs) consisting of magnetic metal nano-granules uniformly distributed in an insulator matrix are one of the best candidates for satisfying these demands because these films have the advantages of high $4\pi M_s$ and high permeability μ of magnetic metal and high ρ of insulator. So far, many kinds of nano-granular films composed of magnetic metals (Fe, Co, FeCo alloys) and various X-(oxide, nitride and fluoride) where X is nonmagnetic elements such as Al, Hf, Zr, Si, etc. have been studied [1,2,7-10].

FeCoB thin films exhibit good soft magnetic properties. However, FeCoB thin films have lower resistivity than that of MIGFs and their magnetic properties are very sensitive to film stress due to large magnetostriction. By considering the unique microstructure of MIGFs, the FeCoB-O system may possess good high frequency properties. Meanwhile, little research has been done on the improvement of soft magnetic properties and high-frequency characteristics of FeCoB–O thin films with changing amounts of oxygen. Therefore, this work has been carried out to examine the effects of oxygen partial pressure on the soft magnetic properties and high frequency characteristics of as-deposited FeCoB-O nano-granular films.

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Experiments

$Fe_{52}Co_{28}B_{20}$-O thin films of 150 nm thickness were deposited on water-cooled glass substrates by RF reactive magnetron sputtering in a Ar + O_2 atmosphere using a composite target. B chips were placed very close to the outer plasma ring on the $Fe_{65}Co_{35}$ alloy target surface. The base pressure of the chamber was below 5×10^{-5} Pa, and the sputtering pressure was kept at ~ 0.4 Pa. The depositions were performed in a static magnetic field of about 500 Oe, which was applied parallel to the substrate plane in order to induce an in-plane uniaxial anisotropy. By varying the oxygen partial pressure, R_{O2} = (O_2 flow rate) / (Ar flow rate + O_2 flow rate) (in %), a series of FeCoB-O thin films were obtained to investigate the soft magnetic properties and high frequency characteristics.

The structure and microstructure were characterized by X-ray diffraction (XRD) (Philips X'Pert model) with Cu K_α radiation and high-resolution transmission electronic microscope (HRTEM), respectively. The composition of the prepared films was analysed by inductive coupled plasma emission spectrometer (ICP). Static magnetic properties were measured by a vibrating sample magnetometer (Lakeshore model 7304). The resistivity was determined by the conventional four-probe method. The film thickness was measured by a surface profile-meter (Dektak 8). The permeability spectra of the samples were obtained from 100 MHz to 5 GHz by a shorted microstrip transmission-line perturbation method [11]. All the above measurements were performed for as-deposited samples at room temperature.

Results and discussion

Fig. 1 shows the dependence of the $4\pi M_s$ and ρ of FeCoB-O thin films on the O_2 partial pressure, R_{O2}. It is seen that $4\pi M_s$ decreases and ρ increases with increasing R_{O2}. These results can be understood easily by the increase of the volume fraction of oxide phase with increasing R_{O2}.

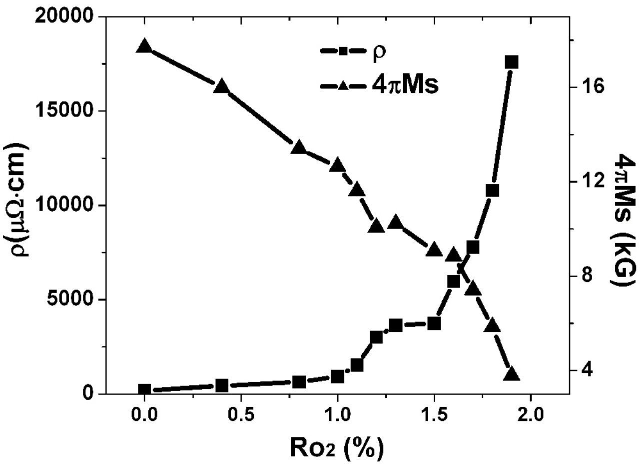

Fig. 1 Dependence of $4\pi M_s$ and ρ of FeCoB-O thin films on R_{O2}.

Fig. 2 depicts the R_{O2} dependence of anisotropy field H_k and coercivity H_c for the as-deposited films, where H_{ce} is the coercivity along the easy axis direction and Hch is the coercivity along the hard axis direction. It can be seen that $H_{ce} < 15$ Oe and $H_k > 60$ Oe in a range $1.1\% \le R_{O2} \le 1.5\%$. Namely, good soft magnetic properties are obtained in this R_{O2} range.

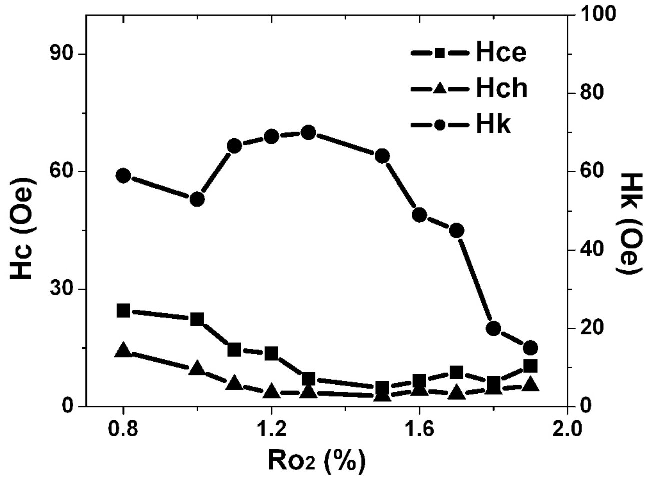

Fig. 2 Dependence of H_k and H_c of FeCoB-O thin films on R_{O2}.

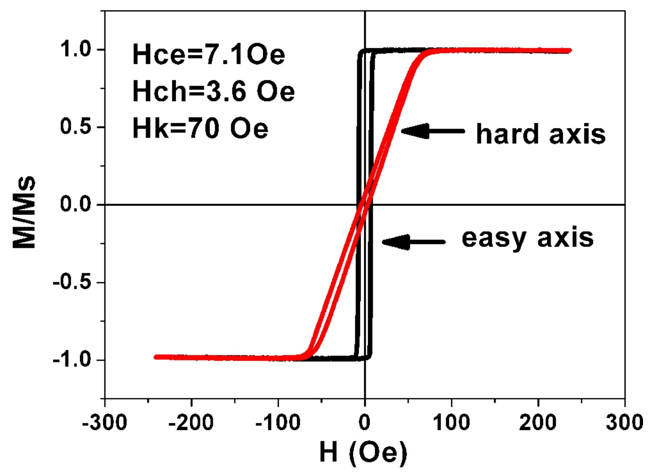

Fig. 3 Easy and hard axis loops for FeCoB-O thin films with R_{O2} = 1.3%.

The hysteresis loop of sample with R_{O2} = 1.3% measured under in-plane fields applied in the directions parallel and perpendicular to the induced anisotropy are shown in Fig. 3. Important magnetic properties are: coercivities in hard and easy axes are H_{ch} = 3.6 Oe and H_{ce} = 7.1 Oe, respectively, in-plane uniaxial anisotropy with H_k =70 Oe, $4\pi M_s$ = 10.2 kG, and ρ reaches 3638 μΩ·cm, which is much higher than that of FeCoB alloy. The good soft magnetic properties of these samples can be understood by the exchange coupling between granules.

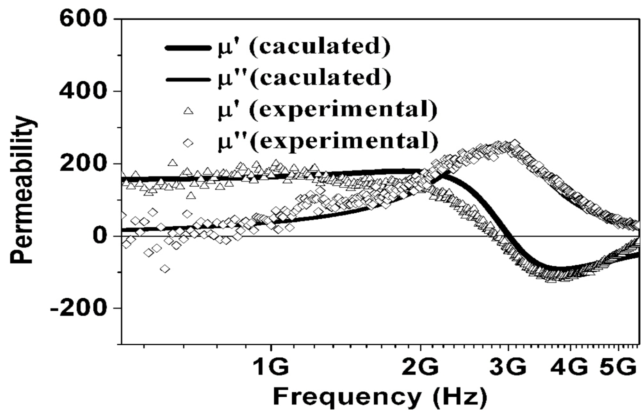

Fig. 4 Permeability characteristic for FeCoB-O thin films with R_{O2} = 1.3%.

Fig. 4 shows the dependence of complex permeability $\mu = \mu' - j\mu''$ on frequency for the film of R_{O2} = 1.3%, where μ' and μ'' represent the real and imaginary part of complex permeability, respectively. It is seen that μ' is more than 145 below 2.0 GHz. While, the imaginary component μ'' gradually increases to a maximum at f = 3.0 GHz, which can be ascribed to the ferromagnetic resonance (FMR) [12]. Since the magnetic crystalline anisotropy of individual particles is averaged due to exchange coupling, a good in-plane uniaxial anisotropy was induced by applying an external magnetic field during deposition. Thus, the behavior of magnetization in high frequency magnetic field in this film can be described by the Landau–Lifshitz equation. The experimental $\mu \sim f$ curves were fitted quite well with the solution [13] of Landau–Lifshitz equation, as shown by the solid lines in Fig. 6. The FMR frequency obtained by this fitting is around 3.0 GHz, consistent with the experimental result. The high FMR frequency implies that the FeCoB-O granular films are promising for application in high frequency range.

Summary

The microstructure, magnetic and high frequency properties of FeCoB-O nano-granular films were systematically investigated. The films consist of FeCo magnetic particles uniformly embedded in an amorphous B-oxide matrix. The good soft magnetic properties have been obtained in a range 1.1% ≤ R_{O2} ≤ 1.5% with H_{ce} < 15 Oe and H_k > 60 Oe. The thin film produced at the R_{O2} = 1.3% has the best soft magnetic properties: $4\pi M_s$ = 10.2 kG, H_{ce} = 7.1 Oe, H_{ch} = 3.6 Oe, H_k =70 Oe, and ρ = 3638 μΩ·cm. The real part of complex permeability of this sample is more than 145 below 2.0 GHz. The ferromagnetic resonance frequency is as high as 3.0 GHz, implying that the film is promising for high frequency applications. Such good soft magnetic properties are ascribed to the exchange coupling among magnetic particles.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (NSFC) (Grant No. 51201083).

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