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Materials Letters 61 (2007) 908–911
materials letters
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High frequency properties of $Ni_{75}Fe_{25}$–SiO_2 granular thin films with very high resistivity

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Received 4 January 2006; accepted 7 June 2006
Available online 27 June 2006

Abstract

Excellent soft magnetic properties have been achieved in low metal volume fraction($x\sim 0.52$) of $(Ni_{75}Fe_{25})_x(SiO_2)_{1-x}$ granular film fabricated by magnetron sputtering. The coercivity of 247 A m^{-1} with very high resistivity ρ over 1.18×10^4 μΩ cm has been obtained. At the frequency lower than 1 GHz, the real part μ' of the complex permeability keeps about 55 and the imaginary part μ'' is less than 2. A combined study of TEM and XRD indicates that the sample consists of $Ni_{75}Fe_{25}$ particles uniformly embedded in insulating SiO_2 matrix. The excellent soft magnetic properties are ascribed to the magnetic dipole interaction between particles. The investigations of field cooled and zero field cooled curves as well as Henkle Plot prove the existence of this intergranular interaction.

Keywords: Thin films; Magnetic materials; High frequency; Very high resistivity

1. Introduction

With the rapid improvement and miniaturization in electromagnetic devices, thin films with high electrical resistivity (ρ), high saturation magnetization ($4\pi M_s$), low coercive force (H_c) as well as high permeability in high frequency range are increasingly in demand. Such films are particularly useful for electromagnetic devices as high frequency components, such as inductive devices and magnetic heads [1–3]. Recently, granular films consisting of nano-ferromagnetic metallic particles distributed uniformly in insulator matrix have attracted much attention because of their excellent soft magnetic properties operating in high frequency range (up to GHz). These films take the advantages of high permeability μ (hence low coercivity) of magnetic metal and high resistivity of insulator, making high μ and high ρ in same material possible. The critical factor leading to good soft magnetic properties in these materials is the interaction between magnetic nanoparticles. Besides, a small magnetic crystalline anisotropy of magnetic particles is still a fundamental requirement for getting good soft magnetic properties.

So far, many kinds of granular films, such as Fe–*M*–O (*M*=Al, Hf, Si, etc.), Co or FeCo-base nano-granular films [4–6], have been reported. However, for most of these systems, the good soft magnetic properties were obtained at a relatively high volume fraction (x) of metal, for example, around x=75.5% Co for Co–Cr–O [7], x=78% Fe for Fe–Al–O [8]. The high x leads to a limitation for attaining very high ρ. While for our samples, the relatively low volume fraction (x=0.52) also exhibits good soft magnetic properties with $H_c\sim 247$ A m^{-1}. At the same time, very high ρ over 1.18×10^4 μΩ cm has been obtained, which effectively depresses the eddy current loss as they are applied in high frequency range. We thought that the magnetic dipole interaction may be responsible for these properties.

In this work, the microstructure and high frequency properties of $Ni_{75}Fe_{25}$–SiO_2 granular film with very low fraction (x=0.52) were investigated and the mechanism of soft magnetic properties was also discussed.

2. Experiments

$Ni_{75}Fe_{25}$–SiO_2 thin films with the thickness of 230 nm were deposited on water-cooled glass substrates in a magnetron co-sputtering system with a base pressure lower than 3×10^{-5} Pa. Ni_3Fe and SiO_2 targets were sputtered in an Ar atmosphere of

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doi:10.1016/j.matlet.2006.06.011

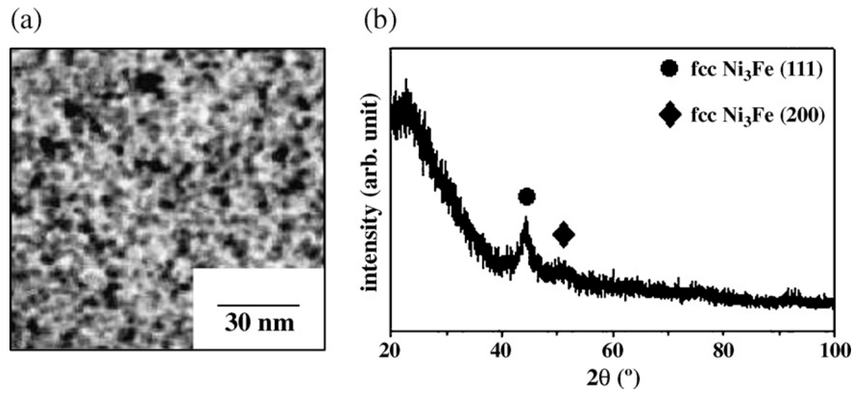

Fig. 1. The bright-field TEM image (a) and X-ray diffraction spectra (b).

0.32 Pa. The composition of the films is controlled by the sputtering power of each target. There is no external magnetic field applied on substrate during deposition. An in-plane uniaxial anisotropy is achieved by the inclined incidence of the sputtering beams [9].

Saturation magnetization, coercivity and in-plane magnetic anisotropy field H_k were measured by vibrating sample magnetometer (VSM) (Lakeshore 7304 model). The field cooled (FC) and zero field cooled (ZFC) curves were obtained by SQUID magnetometer. The composition of the samples was determined by energy dispersive X-ray spectroscopy (EDS). The resistivity was measured by the DC four-probe method. The microstructure was analyzed by X-ray diffraction (XRD) (Philips x Pert model) with Cu Kα radiation and transmission electronic microscope (TEM), respectively. The film thickness was measured by surface profile-meter (Dektak 8). The complex permeability was obtained by using the permeance meter made by Ryowa Electronics Co., which is based on the microstrip line method [10] and works in frequency up to 3 GHz. The measurement was performed along the hard axis of film in plane. All the above measurements were performed for as-deposited samples without any post heat treatment.

3. Results and discussion

Fig. 1 shows the bright field TEM image (a) and X-ray diffraction spectra (b) for $(Ni_{75}Fe_{25})_{0.52}(SiO_2)_{0.48}$ sample. It can be seen that the sample consists of fcc Ni_3Fe particles embedded uniformly in insulating SiO_2 matrix although some small amount of particles are aggregated. No diffraction peaks corresponding to crystalline SiO_2 are detected by XRD and TEM, indicating that the SiO_2 is amorphous. The size distribution for Ni_3Fe nanoparticles is shown in Fig. 2. The curve can be well fitted by Gaussian functions. The width of size distribution is relatively narrow and the average particle size is about 5 nm.

The easy and hard magnetic hysteresis loops at room temperature for this sample is shown in Fig. 3. As is evident in the easy axis hysteresis loop, the as-deposited film is magnetically soft with H_c being only 247 A m^{-1}. The saturation magnetization $4\pi M_s$ and anisotropy field H_k are 0.42 T and 11.5 kA m^{-1}, respectively. It is also found that the hard-axis hysteresis loop is almost closed and linear.

Brown has calculated the critical radius [11] (R_{c1}) of the single domain according to the micro-magnetics principle:

$$R_{c1} = \frac{3.6055}{M_s}\left(\frac{A}{\mu_0}\right)^{1/2} \quad (K > 0) \tag{1}$$

where M_s, A and μ_0 are saturated magnetization, magnetocrystalline anisotropy and vacuum permeability, respectively. The critical radius of Ni_3Fe is 16 nm calculated by expression (1). For our sample with $x=0.52$, the average particle size is around 5.0 nm, smaller than the single domain critical size (~32 nm). Namely, each particle of the sample includes only one single domain. As is well known, an assembly of single domain ferromagnetic particles without interaction among particles usually possesses high H_c and low permeability, due to

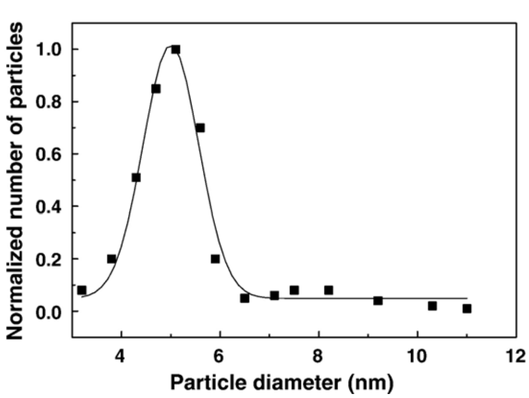

Fig. 2. The size distribution of the Ni_3Fe particles obtained on TEM image. The distribution has been fitted with Gaussian curves.

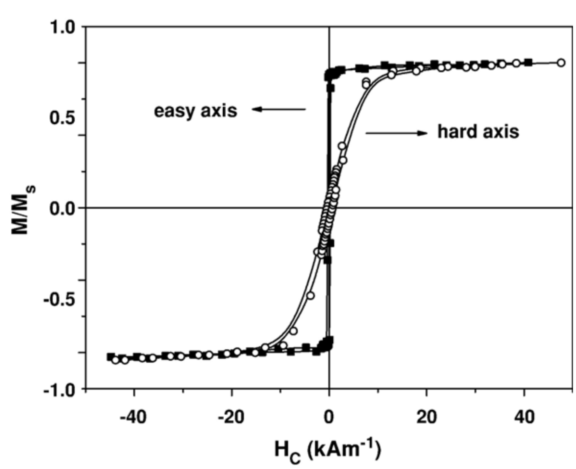

Fig. 3. The easy and hard magnetic hysteresis loops at room temperature.