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Soft magnetic properties of [$Fe_{80}Ni_{20}$-O/NiZn-ferrite]$_n$ multilayer thin films for high frequency application

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Abstract. In this research, a series of [$Fe_{80}Ni_{20}$-O/NiZn-ferrite]$_n$ multilayer thin films with different insulation layer thickness were prepared by magnetron sputtering at room temperature. The high frequency soft magnetic properties of [$Fe_{80}Ni_{20}$-O/NiZn-ferrite]$_n$ multilayer thin films were investigated. It was found that the in-plane magnetic anisotropy field (H_k) and saturation magnetizations ($4\pi M_s$) can be adjusted by changing the insulation layer thickness, and the optimal H_k and $4\pi M_s$ can be obtained as the insulation layer thickness of 2.5 nm. The adjustment of insulation layer thickness is essential to obtain low coercivity (H_c) and high permeability (μ') of the multilayer thin films. The measured resistivity (ρ) of [$Fe_{80}Ni_{20}$-O/NiZn-ferrite]$_n$ multilayer thin films was increased from 211 to 448 μΩ·cm with increasing the insulation layer thickness.

Introduction

In recent years, many electronic devices such as planar inductor, micro transformer and electromagnetic interference suppressor request high frequency soft magnetic materials with high ferromagnetic resonance frequency (f_r) and electrical resistivity [1]. As the working frequency of the material is higher than its ferromagnetic resonance frequency, the magnetic resonance loss would cause a serious decline of permeability (μ) [2]. Besides, the low resistivity (ρ) of traditional soft magnetic thin films would cause a great eddy current loss in high frequency applications, which lead to its high frequency performance reduction [3]. Therefore, how to obtain soft magnetic materials with high resistivity, high ferromagnetic and high permeability under high frequency becomes one of the research focus in present.

As we can obtain from the Landau-Lifshitz-Gilbert equation that the magnetic films which have higher saturation magnetizations ($4\pi M_s$) and adjustable in-plane uniaxial magnetic anisotropy fields (H_k) could get an excellent properties for high-frequency applications. The adjustable f_r and improved static permeability (μ_s) could be achieved since the f_r is proportional to $(H_k \times 4\pi M_s)^{1/2}$ and the μ_s is expressed as $\mu_s = 1+4\pi M_s/H_k$ for thin films with in-plane uniaxial magnetic anisotropy (IPUMA) [4]. Recently, there are many methods to improve ρ and H_k, such as granular metal/insulator composites [5], metal/native-oxide multilayer structure [6] and annealing [7] etc. But the high ρ, large M_s, and adjustable H_k cannot be achieved at same time in the aforesaid methods. In recent years, multilayer thin films composed of magnetic metal or alloy layer and nonmagnetic insulator layer can obtain larger in-plane uniaxial magnetic anisotropy fields than traditional granular film. The magnetic metallic alloys (such as FeNi and FeCo) provides high saturation magnetization in films [8][9], while the addition of nonmagnetic insulator phases (such as Si_3N_4) is an approach to increase the resistivity [10]. It is well known that NiZn-ferrites possess good electrical insulating property and FeNi alloy possesses very high M_s. Therefore, the use of NiZn-ferrite as an insulator phase and FeNi alloy as metal phase for metal/insulator granular films are expected to obtain higher saturation magnetization and resistivity than regular films.

In this work, a series of [$Fe_{80}Ni_{20}$-O/NiZn-ferrite]$_n$ multilayer thin films with different thickness of insulator layers (t) which ranged from 2.5 to 10 nm have been deposited by magnetron sputtering, and their magnetic and electrical properties were investigated. The results demonstrate that the high-frequency soft magnetic properties of the multilayer films can be adjusted by changing the thickness of insulator layers. Moreover, the high $4\pi M_s$ and H_k can be obtained while the resistivity is still relatively larger as t of 2.5 nm. As a consequence, the as-prepared $[Fe_{80}Ni_{20}$-O/NiZn-ferrite$]_n$ multilayer thin films with proper t have great potential application value in GHz frequency range.

Experimental

A high-purity $Fe_{80}Ni_{20}$ (99.99 %) target with a diameter of 76.2 mm and a thickness of 2 mm and a high-purity $Ni_{0.5}Zn_{0.5}Fe_2O_4$ (99.99 %) target with a diameter of 76.2 mm and a thickness of 5 mm were used to deposit $[Fe_{80}Ni_{20}$-O/NiZn-ferrite$]_n$ multilayer thin films onto glass slides and silicon substrates with a thick of 0.5mm by DC and RF magnetron sputtering. The former was connected to a DC power source to sputter the conducting layers and the latter was connected to a RF power source to sputter the insulated layers. The sputtering chamber was evacuated to a background pressure below 7×10^{-4} Pa before deposition. During the sputtering, the Ar gas flow rate and the relative O_2 flow ratio, which could be formulated by $R(O_2)$ = [O_2 flow rate]/[Ar flow rate + O_2 flow rate] (in %) were maintained at 20 sccm (sccm denotes standard-state cubic centimeter per minute) and 1%, respectively. The multilayered structure was obtained by switching on/off the baffle plate that above the targets alternately. The thickness of $Fe_{80}Ni_{20}$-O single layer was well controlled at 5 nm and the NiZn-ferrite single layer was changed from 2.5 to 10 nm by adjusting the sputtering time, respectively. The static magnetic properties of the $[Fe_{80}Ni_{20}$-O/NiZn-ferrite$]_n$ multilayer thin films were characterized by a vibrating sample magnetometer (VSM, Lakeshore 7404) at room temperature. The thicknesses of the films were measured accurately by surface profile-meter (Dektak-III). The structure of the films was analyzed by X-ray diffraction (XRD, Panalytical X'pert-PRO) with Cu K_α radiation. The microwave permeability was measured at frequencies from 100 MHz to 5 GHz by using a vector network analyzer.

Results and Discussion

Fig. 1 shows the XRD patterns of the $[Fe_{80}Ni_{20}$-O/NiZn-ferrite$]_n$ multilayer thin films with t changed from 2.5 to 10 nm. In this figure, the (111) and (200) diffraction peak of fcc-structured FeNi were observed. However, there is no diffraction peak of the NiZn-ferrite can be detected, which indicated that the NiZn-ferrite layers were amorphous phase or nanocrystalline. The intensities of (111) reflections increased slightly with t changing from 2.5 to 10 nm, which may be attributed to a minor crystallinity increase of the thin films.

A classical magnetic hysteresis loops (M-H loops) of the multilayer thin film is shown in Fig. 2. Here the hard axis is along the radial direction of the rounded bearing plate, while the easy axis is along the tangential direction. The saturation magnetization and in-plane uniaxial anisotropy field could be obtained from the magnetic hysteresis loops. From the M-H loops of all films, it is clear that as t = 2.5 nm, the $[Fe_{80}Ni_{20}$-O/NiZn-ferrite$]_n$ multilayer thin film possesses the most excellent H_k of 112.5 Oe. As t increased to 8 nm and the volume fraction of NiZn-ferrite in multilayer films increased, the H_k decreased to 85.8 Oe. Consequently, the high frequency magnetism performance could be controlled by adjusting the thicknesses of insulating layers.

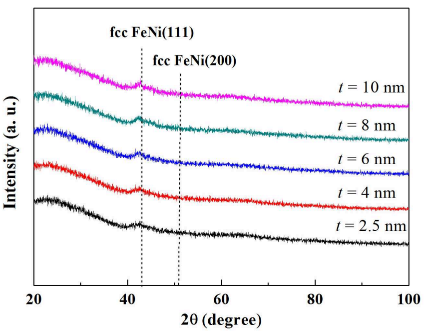

Fig. 1. The XRD patterns

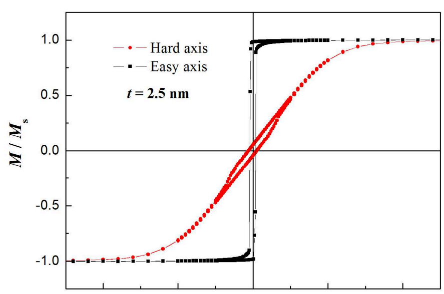

Fig. 2. A classical magnetic hysteresis loops

The coercivity of easy axis and hard axis obtained from the M-H loops was presented in Fig. 3. The coercivity of easy axis and hard axis present a rising trend roughly as t increased from 2.5 to 10 nm, which could be mainly explained by the increase of grain size with changing t from 2.5 to 10 nm as seen from XRD results. In addition, the in-plane uniaxial anisotropy field of this series can also be seen in Fig. 3. From the figure, we can find that H_k of the multilayer films decreased from 112 to 81 Oe as t increased. This phenomenon could be explained by the shape of the grains and the exchange coupling between the neighboring layers. Therefore, the thin films with t of 2.5 nm could have the greatest potential in high frequency applications.

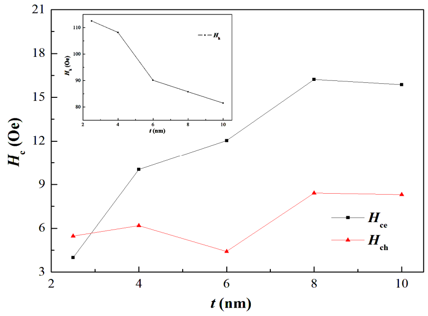

Fig. 3. The H_{ce} and H_{ch} and H_k

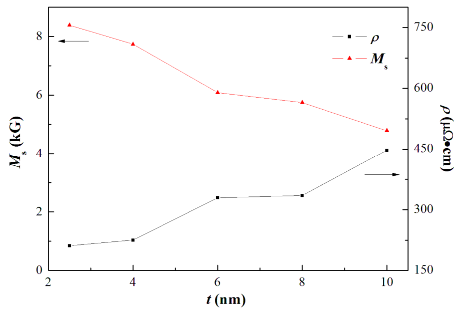

Fig. 4. The $4\pi M_s$ and ρ

The saturation magnetization and electrical resistivity of the multilayer thin films that depend on t were shown in Fig. 4. With increasing t from 2.5 to 10 nm, the $4\pi M_s$ decreased from 8.4 kG to maximum of 4.8 kG. The decrease in $4\pi M_s$ as a function of t could be explained by the decrease volume fraction of the $Fe_{80}Ni_{20}$-O in multilayer films. The resistivity of the multilayer thin films measured by four-point probe at room temperature increased from 211 to 448 μΩ·cm in range of t that changed from 2.5 to 10 nm. The increase of resistivity may be consistent with the increase volume fraction of the NiZn-ferrite in multilayer films.

The minimum value of H_{ce} and H_{ch} and the maximum value of $4\pi M_s$ were all obtained as t of 2.5 nm, which indicates that the $[Fe_{80}Ni_{20}\text{-O/NiZn-ferrite}]_n$ multilayer thin films with t of 2.5 nm would possess most excellent soft magnetic properties. From the Landau-Lifshitz-Gilbert equation we can obtain that the films which have higher $4\pi M_s$ and adjustable H_k could get an excellent properties for high-frequency applications. And meanwhile, the adjustable f_r would be achieved and the static permeability (μ_s) could be improved [4].

Fig. 5 shows the high-frequency real (μ') and imaginary (μ'') permeability spectra of the two samples with t of 2.5 and 10 nm. The FMR frequency (f_r) can be obtained from the permeability spectra. It can be seen that the film with t of 2.5 obtained the real part of permeability $\mu_s = 74.51$ and the resonance frequency $f_r = 3.1$ GHz. When t increased to 10 nm, the film achieved $\mu_s = 58.76$ and $f_r = 3.0$ GHz. The adjustable f_r and improved μ_s mentioned above could be realized as the results shown in fig. 5. The high permeability and resonance frequency indicate that the $[Fe_{80}Ni_{20}\text{-O/NiZn-ferrite}]_n$ multilayer thin films have the potential for applications in GHz frequency range.

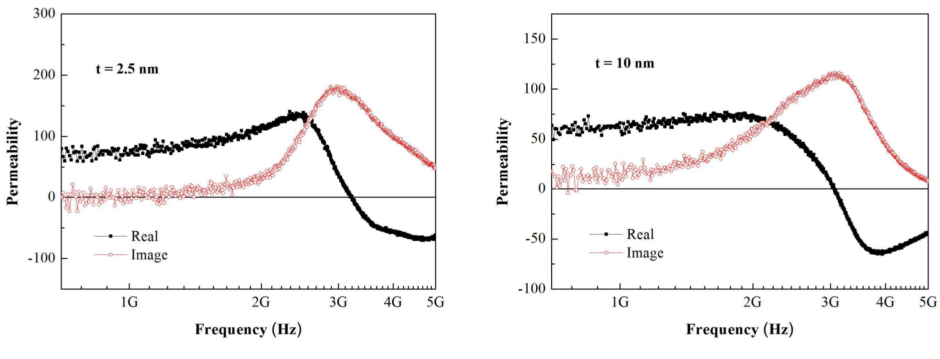

Fig. 5. The high-frequency real (μ') and imaginary (μ'') permeability spectra of the two samples with t of 2.5 and 10 nm.

Conclusions

In this work, a series of $[Fe_{80}Ni_{20}\text{-O/NiZn-ferrite}]_n$ multilayer thin films with different thicknesses of insulator layers that increased from 2.5 to 10 nm were deposited by magnetron sputtering at room temperature. All the films shown high $4\pi M_s$, evident IPUMA and ρ. The H_k of the multilayer films could be adjusted from 112 to 81 Oe as t increased. Moreover, the high permeability and resonance frequency of the multilayer films could also be achieved. The multilayer films grown with the optimal t (t =2.5 nm) exhibited a good comprehensive performance: much higher $4\pi M_s$ of 8.4 kG, relatively lower H_{ce} of 4.0 Oe and H_{ch} of 5.4 Oe and still high ρ of 211μΩ·cm for high frequency applications. All these results imply that the films deposited in this work are promising for high-frequency applications in GHz frequency range.

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