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Electromagnetic characteristics and microwave magnetism of $Fe_{46}Co_{44}B_{10}/SiO_2$ nano-multilayers

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Abstract: $Fe_{46}Co_{44}B_{10}/SiO_2$ nano-multilayers were synthesized by radio frequency magnetron sputtering. The thickness of individual layer was designed and controlled in nano-meter. The effect of thickness of ferromagnetic layer, insulative layer or the total number of layers on the intrinsic characteristics and microwave permeability were investigated respectively. The results show that, saturation magnetization changes obviously with different thicknesses of ferromagnetic layer or insulative layer, but coercivity changes little and remains small. When the thickness of ferromagnetic layer and insulative layer keeps 1.5 and 1.3 nm respectively and the number of the total layers increases from 10 to 90, coercivity reduces and resistivity of the films improves from 0.25 to 2.22 Ω·m. The resonant frequency locates at the point higher than 2 GHz and the imaginary part of complex permeability at 2 GHz is larger than 150. These multilayer films can be applied in the field of micromagnetic devices or anti-interference of electromagnetic wave.

Key words: $Fe_{46}Co_{44}B_{10}/SiO_2$ nano-multilayers; magnetron sputtering; electromagnetic characteristics; complex permeability

1 Introduction

It becomes more and more important to find methods for the absorption of unwanted electromagnetic energy. High permeability magnetic metals used for the control of electro-magnetic interference (EMI) usually have high conductivity and hence support eddy currents, which act to reflect the incident wave before it can be absorbed. Eddy currents can be reduced by fabricating the film in a multilayer design, with the magnetic layer separated by electrically insulating dielectric layers, and also by sectioning the film into electrically isolated regions[1−2]. The frequency-response of complex permeability for $Fe_{46}Co_{44}B_{10}$ films is essentially affected by the film thickness. Large value of imaginary part of complex permeability (μ'' is about 300 at f about 1GHz) distributed over a broad frequency range (Δf=0.5−1.8 GHz), which may become good candidates for application in the control of EMI in the gigahertz range [3−5]. But the resonance frequency is too low to be used in the range higher than 2 GHz. Research proved that multilayer films may present good high frequency properties[6-10].

ZUO et al[11] fabricated discontinuous $[FeCoSi/native\text{-}oxide]_{50}$ multilayer films by DC magnetron sputtering without any post-deposition treatment. The ferromagnetic resonance frequencies of the films increase to 3.9 GHz and the origin of the excellent high-frequency properties in the multilayer films was discussed. MA and ONG[12] exploited a multilayering technique (laminating the magnetic layer with oxide spacers) to improve the magnetic properties in thick CoAlO films. AlO_x and SiO_x were used as the oxide spacing layers. The multilayer films were found to have good soft magnetic properties and gigahertz frequency response (real permeability: ＞200 up to about 2 GHz) when it had a layer thickness of tens of nanometres. MA et al[13] discovered that excellent microwave properties and high electrical resistivity were simultaneously achieved in the discontinuous multilayer structure of $[Co_{44}Fe_{44}B_{12}(0.7\ nm)/MgO(0.4\ nm)]_{40}$ film prepared by means of DC/RF magnetron sputter deposition. The film has a high magnetic loss (μ'' larger than 100 in a

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frequency range from 1.5 to 3.3 GHz), a resistivity of 0.33 Ω·m. It is inferred that the relatively large surface roughness for the discontinuous film is responsible for the wide frequency band of magnetic loss. GREVE et al[14] prepared nanostructured magnetic Fe-Ni-Co/ Teflon multilayers by vapor-phase tandem deposition. The films showed ferromagnetic resonance frequencies from 3.0 to 4.7 GHz and a high-frequency permeability in the range from 100 to 175, while having negligible losses up to 700 MHz and a quality factor Q up to 12 at 1 GHz, and these films could be promising candidates as high-frequency components.

All the researches indicate that for achieving good performances in high frequency range, the difficulties lie in satisfying two sets of conflicting demands: 1) simultaneously achieving soft magnetic properties, high saturation magnetization, and a high resistivity, with the latter required to limit eddy-current losses; and 2) balancing the inherent tradeoff between bandwidth and permeability imposed by the direct and inverse dependences, respectively, of these two parameters on the anisotropy field[15-16].

In this work, we design a new soft magnetic composite system that meets these requirements: a multilayer film, consisting of high-moment $Fe_{46}Co_{44}B_{10}$ layers separated by uitrathin SiO_2 layers. The high-resistivity nonmagnetic insulator oxide layers isolate the metallic layers electrically, while coupling them magnetically and minimizing the decrease in volume-averaged saturation magnetization that exists in traditional metal/ nonmagnetic oxide composites. The resulting anisotropy control, together with the large saturation magnetization, permits the permeability and resonance frequency to be tuned over a wide range to meet specific application requirements.

2 Experimental

The films were deposited on glass substrates with a magnetron sputtering system. The sputtering targets were $Fe_{46}Co_{44}B_{10}$ and SiO_2 with 100 mm in diameter and 5 mm in thickness. Sputter pressure was 0.666 61 Pa and sputter power was set at 50 W. During deposition a magnetic field of about 10 mT was applied to induce an in-plane anisotropy. The substrates were cooled by circulating water. Morphology and microstructure of the sputtered multilayers were analysed by transmission electron microscopy (TEM). The magnetic properties were determined by a vibrating-sample magnetometer (VSM). Resistivity measurements were performed with a four point probe. The complex permeability in the frequency range of 0.05–5 GHz was measured by the microstrip method with a vector network analyzer.

3 Results and discussion

Fig.1 shows the HRTEM morphology of $Fe_{46}Co_{44}B_{10}/SiO_2$ multilayers. It can be seen that the deposited film is morphologically uniform and has repeated multi-layer structure with clear interface. The thickness of each layer is in nanometer.

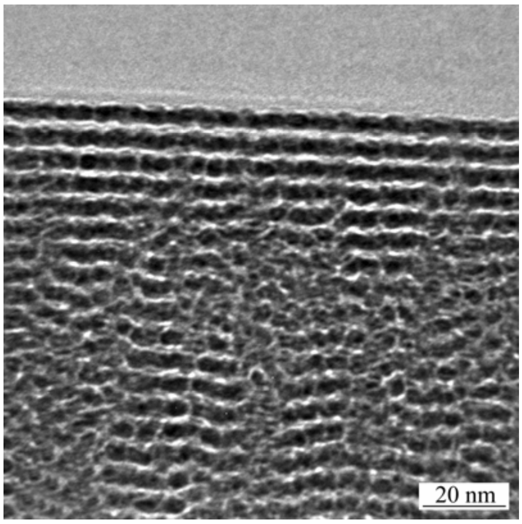

Fig.1 HRTEM photograph of $Fe_{46}Co_{44}B_{10}/SiO_2$ multilayers

Table 1 shows the magnetic parameters such as saturation magnetization and coercivity of $Fe_{46}Co_{44}B_{10}/SiO_2$ multilayers with different thicknesses of magnetic layer. The thickness of each SiO_2 layer is l.0 nm and the total number of layers keeps 30.

Table 1 Magnetic parameters of $Fe_{46}Co_{44}B_{10}/SiO_2$ multilayers with different magnetic layer thicknesses

Magnetic layer thickness/nm	Saturation magnetization/T	Easy axis coercivity/($A\cdot m^{-1}$)
1.0	0.42	96
1.5	0.84	112
2.0	1.06	120
2.5	1.18	120
3.0	1.32	128

The results in Table 1 show that the saturation magnetization of $Fe_{46}Co_{44}B_{10}/SiO_2$ multilayers increases with the increase of magnetic layer thickness, which results from relatively more content of the magnetic CoFeB phase. Additionally, the easy axis coercivity increases slowly, which results from weakening coupling intensity along with thicker magnetic layer. It is also possible that magnetic leakage exists in the interface of layers where there are holes. Thus, the coupling effect between the layers is important to be utilized to adjust the magnetic properties of the $Fe_{46}Co_{44}B_{10}/SiO_2$ multilayers.

Table 2 shows the magnetic parameters such as saturation magnetization and coercivity of $Fe_{46}Co_{44}B_{10}/SiO_2$ multilayers with different thicknesses of insulating nonmagnetic SiO_2 layer. The thickness of each $Fe_{46}Co_{44}B_{10}$ magnetic layer is 2.0 nm and the total number of layers keeps also 30.

Table 2 Magnetic parameters of $Fe_{46}Co_{44}B_{10}/SiO_2$ multilayers with different thickness of SiO_2 layer

SiO_2 layer thickness /nm	Saturation magnetization /T	Easy axis coercivity/(A·m^{-1})
1.0	1.06	120
1.5	0.85	128
2.0	0.73	112
2.5	0.56	144
3.0	0.41	136

It is apparent that the saturation magnetization of $Fe_{46}Co_{44}B_{10}/SiO_2$ multilayers decreases with the increase of insulating nonmagnetic SiO_2 layer thickness, which results from relatively less content of the magnetic CoFeB phase. The easy axis coercivity fluctuates near 127 A/m and keeps values less than 159 A/m when the SiO_2 layer thickness changes from 1.0 to 3.0 nm. So it is logical to deduce that the coupling intensity between the adjacent layers keeps strong though the thickness of SiO_2 layer changes obviously. The strong coupling intensity between the layers may restrain dispersion of magnetic moment from the easy axis. So it is also effective to regulate the magnetic properties of $Fe_{46}Co_{44}B_{10}/SiO_2$ multilayers by changing SiO_2 layer thickness.

The total layer number of magnetic multilayers is affirmatively an important factor to affect the magnetic properties. Table 3 shows the electromagnetic parameters of coercivity and resistivity change with different total layer numbers of $Fe_{46}Co_{44}B_{10}/SiO_2$ multilayers. The layer thicknesses of $Fe_{46}Co_{44}B_{10}$ and SiO_2 are 1.5 and 1.3 nm, respectively.

Table 3 shows that the easy axis coercivity increases

Table 3 Electromagnetic parameters of $Fe_{46}Co_{44}B_{10}/SiO_2$ multilayers with different total layer numbers

Total layer number	Easy axis coercivity/(A·m^{-1})	Resistivity/(Ω·m)
10	184	0.25
20	144	0.76
30	112	0.83
50	104	1.21
70	96	2.13
90	80	2.22

with more repeated layers. HRTEM photograph of Fig.1 shows that clear and flat interfaces exist between the layers. The insulating nonmagnetic SiO_2 layers in nanometer ensure that strong coupling effect keeps between layers. Increment of the total layer number makes more layers of $Fe_{46}Co_{44}B_{10}$ magnetic phase contribute to the coupling effect. Thus, soft magnetic properties get enhanced. Furthermore, the resistivity of $Fe_{46}Co_{44}B_{10}/SiO_2$ multilayers gets improved noticeably with the increase of the total layer number, which may be attributed to stronger scattering of electrons by the interfaces. It is significative to balance the electromagnetic performances by optimizing the thickness of each layer and the total number of repeated layers. Good soft magnetic properties along with high resistivity are basal to achieve fine electromagnetic performances in high frequency range.

The microwave complex permeability spectra of $Fe_{46}Co_{44}B_{10}/SiO_2$ multilayers with different total layer numbers are shown in Fig.2. The thickness of each $Fe_{46}Co_{44}B_{10}$ layer and SiO_2 layer keeps 1.5 and 1.3 nm respectively for the two $Fe_{46}Co_{44}B_{10}/SiO_2$ film samples. It is obvious that the resonant frequency of sample with 30 layers locates at the point lower than 2 GHz(Fig.2(a)), but the resonant frequency of sample with 60 layers is higher than 2 GHz (Fig.2(b)). The real part μ' of the

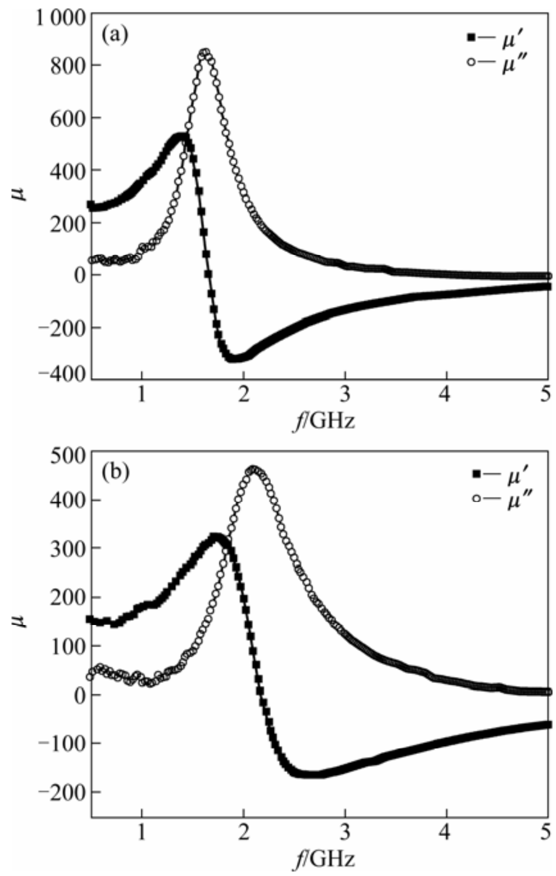

Fig.2 Permeability spectra of $Fe_{46}Co_{44}B_{10}/SiO_2$ nano-multilayers with different numbers of layers: (a) 30; (b) 60

complex permeability in the lower frequency range is larger than 200 for the sample with 30 layers (Fig.2(a)) and that of the sample with 60 layers is smaller than 200 (Fig.2(b)). The imaginary part μ'' values of the complex permeability for the two samples are all smaller than 50 in the frequency range lower than 1 GHz. It is inferred that the anisotropy field of sample with 60 layers is stronger. μ'' at 2 GHz of the two samples are all larger than 150. Thus, these $Fe_{46}Co_{44}B_{10}/SiO_2$ multilayer films can be applied in the field of micromagnetic devices or anti-interference of electromagnetic wave.

4 Conclusions

1) $Fe_{46}Co_{44}B_{10}/SiO_2$ nano-multilayers are prepared by radio frequency magnetron sputtering and the thickness of individual layer is controlled in nano-meter.

2) Saturation magnetization changes obviously with different thicknesses of ferromagnetic layer or insulative layer, but coercivity changes little and remains small.

3) Coercivity reduces and resistivity improves from 0.25 to 2.22 $\Omega\cdot$m when the total number of layers increases from 10 to 90.

4) The resonant frequency locates at the point higher than 2 GHz and the imaginary part of complex permeability at 2 GHz is larger than 150 by optimization for the thickness of ferromagnetic layer, insulative layer and the total number of layers.

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