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Microwave properties and surface topography of soft magnetic films with high resistivity*

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A single layer of CoFeB and a multilayer of CoFeB–MgO films are prepared by means of DC/RF magnetron sputter deposition. The excellent microwave properties and high electrical resistivity are simultaneously achieved in the discontinuous multilayer structure of $[Co_{44}Fe_{44}B_{12}(0.7\,nm)/MgO(0.4\,nm)]_{40}$ film. This film has a high permeability ($\mu\prime$) (larger than 100 below 2.1 GHz), a high magnetic loss (μ'') (larger than 100 in a range from 1.5 to 3.3 GHz), a resistivity of $3.3\times10^3\,\mu\Omega\cdot$ cm, a saturation magnetization of 1.2 T, and an in-plane uniaxial anisotropy field of 5.5 kA/m. The microstructure and the surface topography of the film are also analysed. The relatively large surface roughness for the discontinuous film is responsible for the wide frequency band of magnetic loss. The magnetic loss and the high resistivity indicate that the discontinuous CoFeB–MgO multilayer film has potential applications in microwave absorbers and electromagnetic interference (EMI) shielding materials in a GHz frequency range.

Keywords: soft magnetic films, microwave properties, resistivity, roughness
PACC: 7570, 7530G, 7540G, 7550B

1. Introduction

As the requirement for a high operating frequency and degree of integration in electronic devices rises, electromagnetic noise and electromagnetic interference (EMI) increase accordingly. A lot of research has been carried out to develop soft magnetic thin films for suppressing EMI effects, such as near-field electromagnetic noise suppressors,[1] microwave absorbers,[2] *et al* A more detailed mechanism of the countermeasure for electromagnetic noise emission in magnetic films, the mechanism that is for suppressing EMI effects, was briefly explained elsewhere.[3] Soft magnetic nano-granular thin films have been extensively studies as microwave materials useful in a GHz range.[2,4–6] As is well known, films required for high frequency applications must have the following magnetic properties: high saturation magnetization $4\,\pi M_s$,[7] appropriately anisotropic field H_k that increases the self-resonant frequency, and high electrical resistivity ρ that is expected to suppress eddy current loss and is favourable to electromagnetic matching for removing the stub effect.[8,9] Magnetic nano-granular films which comprise nanometre-scale ferromagnetic metal particles dispersed in an insulating amorphous phase may present not only excellent soft magnetic properties[10] but also high electrical resistivity, thus it is possible to balance electrical and magnetic capability in the microwave frequency range. In the present paper, electromagnetic and microwave properties of discontinuous multilayer films comprising amorphous CoFeB nano-granules around nanometre size dispersed in an insulating MgO matrix are investigated, and the microstructure and the surface topography of the single layer CoFeB and multilayer CoFeB–MgO films are also analysed.

2. Experimental details

Single layer CoFeB and multilayer CoFeB–MgO films were deposited onto a rotating Coring 7059 glass substrate cooled with water by sequential magnetron sputtering from two separate targets of MgO (99.99%) and $Co_{40}Fe_{40}B_{20}$ (99.99%) covered with 6

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Co and 6 Fe chips (1.5 mm × 10 mm) for adjusting the composition of films, thus the atomic ratio of magnetic layer was fixed at $Co_{44}Fe_{44}B_{12}$. The base pressure was below 4×10^{-5} Pa prior to deposition. Sputtering was carried out in an Ar atmosphere with a pressure of 0.3 Pa at ambient temperature, with RF and DC input powers being 100 and 38 W for MgO and CoFeB targets, respectively. The resulting deposition rates were 1.8 nm/min for MgO and 5.1 nm/min for CoFeB. The thickness of each sublayer was determined from the deposition time calculated from the deposition rate controlled by computer. The structure of the multilayer film was denoted as $[Co_{44}Fe_{44}B_{12}(x\,\mathrm{nm})/MgO(y\,\mathrm{nm})]_n$ composed of n bilayers of CoFeB–MgO. A magnetic field of 24 kA/m was applied during deposition in order to induce a uniaxial anisotropy in the film plane. The above samples were prepared for magnetic and electric characterizations. The films were also deposited on amorphous carbon membrane for the analysis of the film structure by transmission electron microscopy (TEM).

The microstructure of the films was analysed by JEM-2010 high-resolution TEM. The crystalline structure of the films was determined by $2\theta/\theta$ x-ray diffraction (XRD) with Cu Kα radiation. Saturation magnetization $4\pi M_s$, coercivity H_c and in-plane magnetic anisotropy field H_k were measured by a DMS Model 4 HF vibrating sample magnetometer (VSM) of ADE Technologies, at room temperature. The surface topography and the roughness of the films were analysed with an atomic force microscope (AFM). The electrical resistivity ρ of the films was measured by the conventional four-probe method. Complex permeability in a frequency range of 0.5–5 GHz was measured along the hard axis in-plane of films by the microstrip method[11] with an HP8722ES vector network analyser. All the above measurements were performed on as-deposited films.

3. Results and discussion

A bright field TEM plane micrograph and the corresponding selected area diffraction (SAD) pattern of the film with a sandwiched structure: $MgO(0.4\,\mathrm{nm})/Co_{44}Fe_{44}B_{12}(0.7\,\mathrm{nm})/MgO(0.4\,\mathrm{nm})$ are shown in Fig.1. The film is discontinuous and forms a granular structure, and the diameters of metallic and insulating particles are both near 5 nm. Owing to the fact that the metallic component has much higher surface tension than the insulating one, the metal layer does not wet the oxide and, below some thickness, it breaks up into almost spherical nano-granules.[12] But the metallic particles are not completely isolated: some of them impinge on each other because the volume fraction of the metallic phase approaches the percolation threshold. Thus the films exhibiting soft magnetic properties could be obtained by many sequential depositions of the granular bilayers of CoFeB–MgO since one would expect that the particles are magnetically coupled. Moreover, in the corresponding SAD pattern of this film as shown in the inset of Fig.1, there appears only one broad diffuse diffraction ring. This indicates that the film is amorphous, which is consistent with the result of the XRD of $[Co_{44}Fe_{44}B_{12}(0.7\,\mathrm{nm})/MgO(0.4\,\mathrm{nm})]_{40}$ film (data not shown). Hence, the magnetocryalline anisotropy is essentially absent for both of films, due to a lack of long-range ordering in the atomic arrangement. This is favourable to obtaining soft magnetic properties.

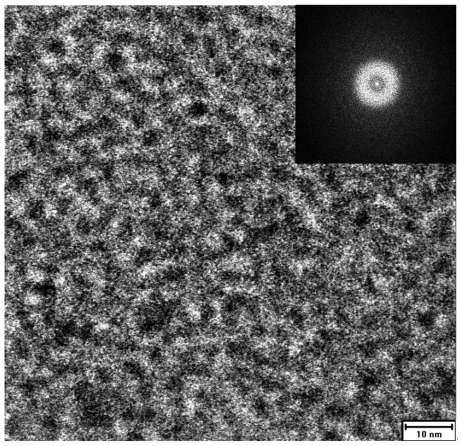


Fig.1. Bright field TEM micrograph of the $MgO(0.4\,\mathrm{nm})/Co_{44}Fe_{44}B_{12}(0.7\,\mathrm{nm})/MgO(0.4\,\mathrm{nm})$ film, where the inset indicates SAD patterns showing the film to be amorphous.

The $[Co_{44}Fe_{44}B_{12}(0.7\,\mathrm{nm})/MgO(0.4\,\mathrm{nm})]_{40}$ multilayer and CoFeB single layer films are deposited based on the above discussion. Their magnetic hysteresis loops are shown in Fig.2. For both of them, the easy axis is shown to be nearly parallel to the direction of an external field applied during deposition, and the hard axis is perpendicular to the easy axis. The easy axis loop is very square while the hard axis loop is nearly closed and almost linear. Hence, the value of the in-plane uniaxial magnetic anisotropy field, H_k, estimated from the magnetic hysteresis loops in Fig.2, is as high as about 5.5 kA/m for the dis-

continuous CoFeB–MgO multilayer film. This observed field-induced anisotropy is most likely to be due to the alignment of local atomic-pair ordering in the amorphous matrix. The small value of coercivity is attributed to the existence of some magnetic interaction among the particles. When the volume fraction of the metallic phase approaches the percolation threshold, the formation of a connecting network of small particles starts to occur. Under such a condition, the particles are magnetically coupled, so the film shows good soft magnetic properties. However, it should be noted that the discontinuous CoFeB–MgO multilayer film possesses higher coercivity than the CoFeB single layer, which can cause a higher loss in high frequency applications. In addition to the static magnetic properties, the resistivity of $[Co_{44}Fe_{44}B_{12}(0.7\,nm)/MgO(0.4\,nm)]_{40}$ film has also been measured to be $3.3\times10^3\,\mu\Omega\cdot$cm, which is more than forty five times higher than the one of single CoFeB layer films with a similar thickness, around $72.6\,\mu\Omega\cdot$cm for our film. The high resistivity of $[Co_{44}Fe_{44}B_{12}(0.7\,nm)/MgO(0.4\,nm)]_{40}$ film is favourable to electromagnetic matching and also to the suppressing of the eddy current effect, which is disadvantageous to improving microwave properties of the film.

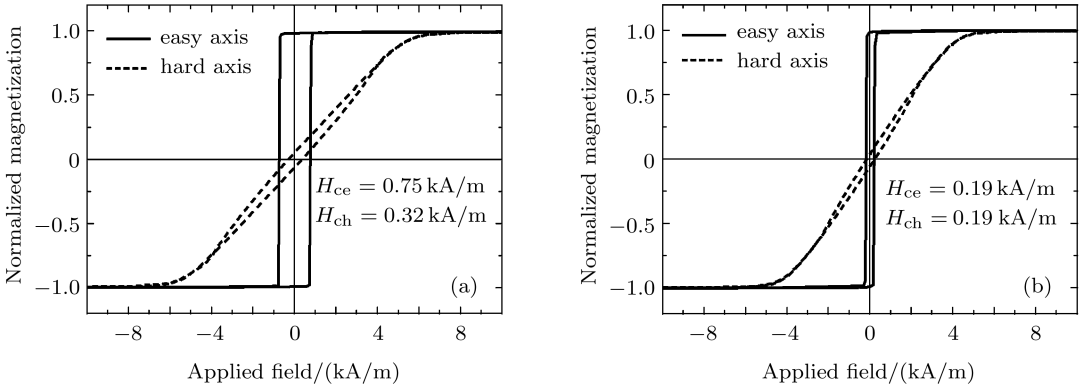


Fig.2. Easy and hard magnetic hysteresis loops of $[Co_{44}Fe_{44}B_{12}(0.7\,nm)/MgO(0.4\,nm)]_{40}$ multilayer film (a) and $Co_{44}Fe_{44}B_{12}$ single layer film (b).

The discontinuous multilayer film discussed in the present paper possesses not only relatively large saturation magnetization ($4\pi M_s > 1.2$ T) but also high resistivity ($\rho > 3.3\times10^3\,\mu\Omega\cdot$cm). Furthermore, the strengthened interaction between magnetic particles in nanometre size makes the rotation magnetization process take place more easily. Thus, the film should present not only excellent soft magnetic properties but also high permeability.

Complex permeability spectra in a range of 0.5–5 GHz for $[Co_{44}Fe_{44}B_{12}(0.7\,nm)/MgO(0.4\,nm)]_{40}$ film were measured as shown in Fig.3. The spread of data in a relatively low frequency range is attributed to the error in measurement.[13] For the $[Co_{44}Fe_{44}B_{12}(0.7\,nm)/MgO(0.4\,nm)]_{40}$ film, the real part of complex permeability μ' is nearly a constant of about 170 below 1.8 GHz and larger than 100 until 2.1 GHz, while the imaginary part μ'' is larger than 100 in a range from 1.5 to 3.3 GHz for this film. Considering $4\pi M_s = 1.2$ T and $H_k = 5.5$ kA/m measured

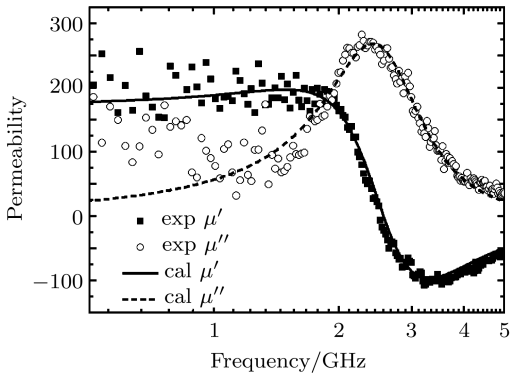


Fig.3. Complex permeability spectra of $[Co_{44}Fe_{44}B_{12}(0.7\,nm)/MgO(0.4\,nm)]_{40}$ films, where symbols "■" and "○" denote measured data of real and imaginary parts of the complex permeability and the solid and the dashed lines represent corresponding calculated results.

by the VSM for the film, and taking α as a fitting parameter, the experimental μ–f curves were fitted to the Landau–Lifshitz–Gilbert formula well[14] as shown by the solid and dashed lines in Fig.3. The ferromagnetic resonance (FMR) frequency obtained by this fitting is around 2.3 GHz, which is in agreement with the experimental results. The damping factor α is fitted as 0.05, much larger than the one of single CoFeB layer films (a typical value of α is 0.009 fitted by data of single CoFeB layer with a similar thickness). The reason for this is that the addition of dielectric phase MgO to magnetic phase CoFeB leads to more defects and impurities in the film, which results in many domain walls pinned and high coercivity as compared with those of CoFeB single layer, which can be seen in Fig.2. Moreover, the discontinuous $[Co_{44}Fe_{44}B_{12}(0.7\,nm)/MgO(0.4\,nm)]_{40}$ multilayer film is more inhomogeneous and shows larger surface roughness. The AFM surface image of the film is shown in Fig.4. The obtained root mean square (RMS) roughness is around 0.31 nm (Figs.4(a) and 4(c)), and it is approximately twice larger than the

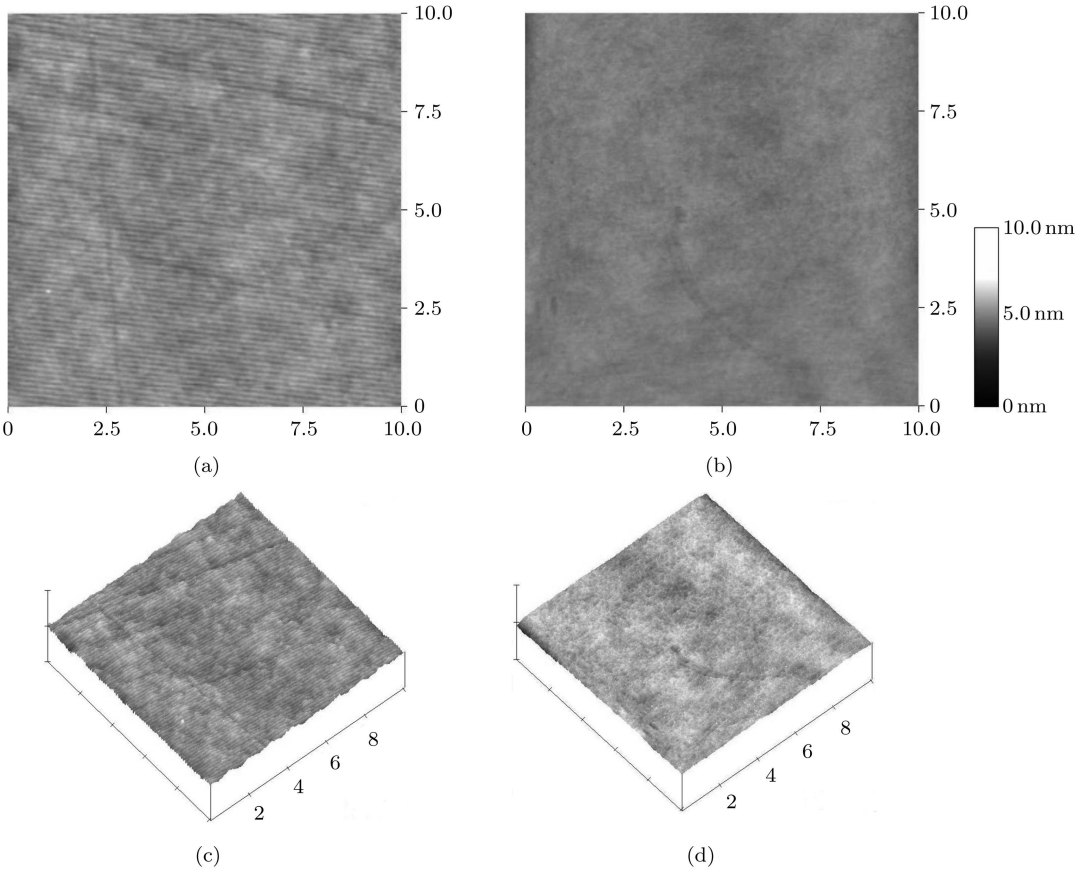


Fig.4. $10\times10\,\mu m^2$ AFM images of $[Co_{44}Fe_{44}B_{12}(0.7\,nm)/MgO(0.4\,nm)]_{40}$ film in (a) and (c), and $Co_{44}Fe_{44}B_{12}$ single layer in (b) and (d), showing roughness analysis and surface topography.

one of the CoFeB single layer film with a similar thickness of 0.16 nm (Figs.4(b) and 4(d)). The relatively large surface roughness leads to anisotropy dispersion in the plane of the film, which increases the damping factor α, and thereby increasing the width of resonance peak for imaginary part (μ'') of complex permeability.[15] Hence, the imaginary part of complex permeability has a large value in a broader frequency range, that is, the bandwidth of magnetic loss is broadened. It is, therefore, attractive to applications of electromagnetic noise suppression.

The combination of relatively high resistivity, moderate FMR frequency, large microwave permeability and high magnetic loss in a broad frequency range

makes this film potentially useful for serving as EMI shielding materials or microwave absorber design.

4. Conclusions

The microstructure, surface topography, electromagnetic and microwave properties of discontinuous $[Co_{44}Fe_{44}B_{12}(0.7\,nm)/MgO(0.4\,nm)]_{40}$ multilayer film have been investigated. It possesses a high electrical resistivity of $3.3\times10^3\,\mu\Omega\cdot$cm and a high saturation magnetization of 1.2 T along with a high in-plane uniaxial anisotropy field of 5.5 kA/m. Moreover, in the microwave property, this film exhibits high magnetic loss (μ'') as well as high permeability (μ') in a GHz frequency range. This is mainly due to the relatively large surface roughness and inhomogeneity detected by AFM. The real part of complex permeability μ' is nearly a constant of about 170 below 1.8 GHz and larger than 100 until 2.1 GHz, while the imaginary part μ'' is larger than 100 in a range from 1.5 to 3.3 GHz for this film. Thus the presented film may serve as EMI shielding materials and microwave absorbers in the GHz frequency range.

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