U-8

A model for asymmetric giant magnetoimpedance in field-annealed Co-based amorphous ribbons

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1. Introduction

Much attention has been paid recently to the asymmetric giant magnetoimpedance (GMI) effect, which is promising for the development of weak magnetic field sensors. A very large asymmetric GMI has been observed in Co-based amorphous ribbons annealed in air in the presence of a weak magnetic field [1–3]. The asymmetry of the GMI profile has been ascribed to a hard magnetic phase, which appears due to the surface crystallization of an amorphous ribbon [2]. The exchange coupling between crystalline and amorphous phases produces an effective bias field that is responsible for the asymmetric GMI [1,2]. Although the asymmetric GMI has been studied experimentally quite well, the satisfactory theoretical explanation of the effect is still missing. We develop a phenomenological model to describe the field and frequency dependences of the asymmetric GMI in field-annealed amorphous ribbons taking into account both the domain-wall motion and magnetization rotation contributions to the transverse permeability.

2. Model

The relationship between the impedance and magnetic permeability of a conductor can be described in terms of the classical skin effect. Under some simplifying assumptions, the impedance Z of an amorphous ribbon can be presented in the following form:

$$Z = R_{DC}[(1-i)d/2\delta]\times\coth[(1-i)d/2\delta], \tag{1}$$

where $R_{DC}=l/\sigma dw$ is the DC ribbon resistance; l, w, d and σ are the ribbon length, width, thickness and conductivity, respectively; $\delta=c/(4\pi^2 f\sigma\mu)^{1/2}$ is the skin depth; c is the velocity of light; f is the current frequency and μ is the transverse permeability.

To calculate the transverse permeability, it is assumed that an amorphous ribbon has a simplified domain structure, which consists of two different types of domain [4]. The ribbon has uniaxial anisotropy with the anisotropy field H_a, and the anisotropy axis makes the constant angle ψ with the longitudinal direction. Due to the magnetostatic or magnetoelastic coupling between an amorphous phase and a surface crystalline layer, an effective bias field H_b appears in the amorphous region. The bias field is in the opposite direction with respect to the crystalline field in the surface layer [2,3]. We consider for simplicity that H_b and the bias field angle φ are constant over the ribbon thickness.

The equilibrium angles of the magnetization vectors in the domains, θ_1 and θ_2, and the equilibrium domain-wall displacement z_0 can be found by minimizing the free energy, which yields

$$H_a \sin(\theta_j-\psi)\cos(\theta_j-\psi)+H_b\sin(\theta_j-\varphi)+H_e\sin\theta_j=0,\quad j=1,2, \tag{2}$$

$$z_0=(aM/\beta)[H_e\{\cos\theta_1-\cos\theta_2\}+H_b\{\cos(\theta_1-\varphi)-\cos(\theta_2-\varphi)\} -(H_a/2)\{\sin^2(\theta_1-\psi)-\sin^2(\theta_2-\psi)\}], \tag{3}$$

where H_e is the external magnetic field, M is the saturation magnetization, a is the domain width at zero external magnetic field and β is the domain-wall pinning parameter.

The contribution to the susceptibility from the magnetization rotation can be calculated by solving the linearized Landau–Lifshitz equation. The average transverse rotational susceptibility, $<\chi_{rot}>$, is found by averaging the susceptibility tensor components [5] over domains taking into account the equilibrium domain-wall displacement. The contribution from the domain-walls motion to the transverse susceptibility, χ_{dw}, can be found by means of the analysis of the domain wall dynamics in the field of AC current. Finally, the transverse permeability of the ribbon is calculated as $\mu=1+4\pi(\chi_{dw}+<\chi_{rot}>)$.

3. Results and discussion

The calculated GMI profiles are shown in Fig. 1 as a function of the external magnetic field H_e at two current frequencies for different values of the effective bias field H_b. At low frequencies, the main contribution to the permeability is due to the domain-walls motion, and the GMI response shows the single-peak behavior. If the bias field equals zero, the GMI profile is symmetric with respect to the external field. In the presence of the bias field, the peak value of the GMI response shifts towards positive fields, and the GMI profile becomes asymmetric and exhibits step-like increase near peak field (so called "GMI valve"). The asymmetry and the magnitude of the GMI response increase with the bias field.

At high frequencies, the domain-walls motion is damped by eddy currents, and the magnetization rotation process determines the permeability. The effect of the domain-walls motion on the GMI is essential only in the vicinity of the field, at which the impedance has minimum. The GMI profile shows the two-peak behavior, and the profile is asymmetric. The asymmetry growths with the bias field H_b, the negative field peak decreases and the positive field peak increases.

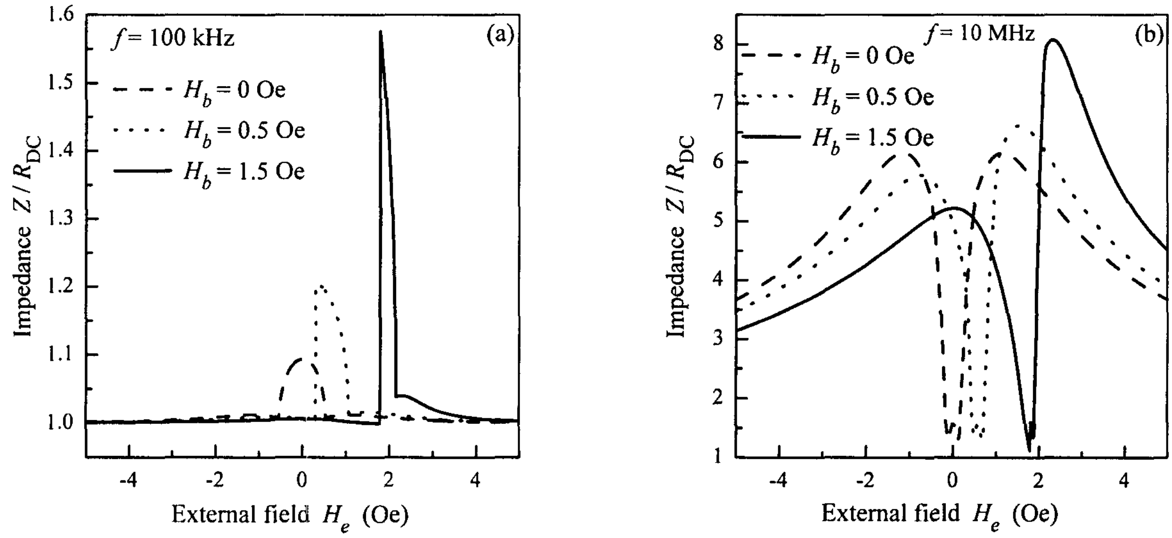

Fig. 2. Dependence of Z on H_e. Parameters of ribbon used for calculations are d=20 μm, a=5 μm, $\sigma=10^{16}$ s^{-1}, M=600 G, H_a=1 Oe, $\beta / MH_a a$=0.5, the damping parameter α=0.1, ψ=0.35π, φ=1.05π.

The model proposed allows one to describe the changes in the GMI profile with a variation of the current frequency. The calculated GMI response is of the same order of the magnitude as that observed experimentally [3]. However, the impedance drops more sharply at positive fields in comparison with the experimental data. This disagreement may be related to the spatial distribution of the bias field, which is neglected in the model. Note that we assume that the direction of the crystalline field in the surface layer differs from that of the annealing field. This fact may be attributed to the influence of the uniaxial anisotropy in the amorphous phase on the crystallization process in the surface layer.

4. Conclusions

The effective bias field appearing due to the exchange coupling between the crystalline layer and amorphous phase results in the asymmetry of the GMI profile. It is shown that at sufficiently low frequencies, the GMI profile exhibits a drastic step-like change in the impedance near zero field ("GMI valve") due to the effect of the domain-walls motion. At high frequencies, the magnetization rotation process becomes dominant, and the GMI profile shows the asymmetric two-peak behavior. The calculated dependences are in a good agreement with the GMI profiles observed in the experiments [1–3].

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References

[1] C.G. Kim, K.J. Jang, Y.C. Kim, S.S. Yoon, J. Appl. Phys. 85 (1999) 5447.
[2] C.G. Kim, C.O. Kim, S.S. Yoon, J. Magn. Magn. Mater. 249 (2002) 239.
[3] Y.W. Rheem, K. Jin, S.S. Yoon, C.G. Kim, C.O. Kim, IEEE Trans. Magn. 39 (2003) 3100.
[4] D. Atkinson, P.T. Squire, J. Appl. Phys. 83 (1998) 6569.
[5] D.P. Makhnovskiy, L.V. Panina, D.J. Mapps, Phys. Rev. B 63 (2001) 144424.