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The variation of linewidth in exchange coupled bilayer films with stress anisotropy

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ABSTRACT

The frequency linewidth and the field linewidth in ferromagnetic/antiferromagnetic bilayer films with stress anisotropy have been investigated by using ferromagnetic resonance method. The effects of the stress anisotropy for in-plane anisotropy, weak and strong perpendicular anisotropy on linewidth are observed. It is found that the frequency and the field linewidth all increase for in-plane and weak perpendicular anisotropy, as the stress anisotropy field increases. And furthermore, the stress anisotropy field affects obviously the frequency and the field linewidth for unsaturation field.

1. Introduction

Since the exchange bias of exchange coupling at the interface first observation by Meiklejohn and Bean [1], the phenomenon studied and explained in recent years [2–7]. As a result, ferromagnetic (F)/antiferromagnetic (AF) bilayer film has attracted much attention because the exchange bias of exchange coupling at the interface. As we all know, ferromagnetic resonance (FMR) is a practical method for researching multilayer films, and it was found by Griffiths [8] and formally continued by Kittel [9] and Suhl [10], characterizing properties of ferromagnetic materials, such as effective magnetization, anisotropy fields, gyromagnetic ratio, magnetic coupling, magnetic relaxation [11–14], phase transition and extrinsic linewith [15–19]. The frequency and field linewidths were originally studied by Patton [20]. Recently, many theoretical and experimental researches also have been related to explain the frequency linewidth and the field linewidth by FMR means. In other words, the linewidth has been the research emphasis of a lot scientific research [21–30]. It is widely believed that the frequency and field linewidths are integrated to each other. Stress anisotropy plays an irreplaceable role in the frequency and the field linewidth. During the past several decades, the rapid development in FMR drives researches to detect the effect of intrinsic stress and strain parameters of films. But the validity of the frequency and field linewidths conversion relation has not been absolutely confirmed for perpendicular anisotropy. This paper aims to illustrate the effects of stress for the frequency and field linewidths characteristics of an exchange coupled bilayer thin films with tilted out-of-plane anisotropy easy axis.

The paper is organized as follows. The analytic derivation will be obtained in Section 2. Sections 3 and 4 discussed the effect of stress anisotropy for two cases of interest, i.e., the in-plane anisotropy axes and the perpendicular anisotropy axis for weak and strong perpendicular anisotropy. Section 5 gives a summary and conclusion.

2. Model and calculation procedure

The systems under research here are the coupled bilayer. The two thin layers are supposed to F and AF. The two films F/AF bilayer film are assumed to lie in the x–y plane, with the z axis normally directed. The exchange anisotropy along the x axis is modeled in terms of an effective field H_E. Without loss of generality, the anisotropy axis of out-of-plane is taken in the x–z plane, making an δangle with the z axis. The magnetization M of the ferromagnetic layer is defined, in spherical coordinates, by the polar and the azimuthal angles θ and ϕ. The polar and the azimuthal angles of the stress anisotropy and the external applied magnetic field are confirmed by θ_σ, ϕ_σ and θ_H, ϕ_H, respectively. With all these consideration, the total free energy per unit volume in F/AF system can be explicitly written as

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$$E = -MH\left[\sin\theta\sin\theta_H\cos\left(\phi-\phi_H\right) + \cos\theta\cos\theta_H\right] - 2\pi M^2\sin^2\theta - MH_E\sin\theta\cos\phi + K\left[\sin^2\theta\left(\cos 2\delta + \sin^2\delta\sin^2\phi\right) - \frac{1}{2}\sin 2\theta\sin 2\delta\cos\phi\right] - \frac{3}{2}\lambda_s\sigma\left(\sin\theta_\sigma\cos\phi_\sigma\sin\theta\cos\phi + \sin\theta_\sigma\sin\phi_\sigma\sin\theta\sin\phi + \cos\theta_\sigma\cos\theta\right)^2, \tag{1}$$

Here K is the magnto-crystalline anisotropy constant, λ_s and σ is magnetostriction coefficient and stress intensity, respectively. In the case of bilayer coupling, we limit magnetostriction of the film is isotropic. The first line in the right side of above equation is the Zeeman energy, the shape anisotropy and the interfacial exchange anisotropy energies are displayed in the second and third terms, respectively. The fourth term expresses the magneto-crystalline anisotropy energy with an δ tilted angle from the normal of the film, and the last term denote the stress anisotropy energy. From Smit and Beljer's resonance condition [31], in the circumstances of $\theta_H = \pi/2$ and $\theta_\sigma = \pi/2$, $\phi_\sigma = 0$, the dispersion relation for F/AF system can be calculated into

$$\left(\frac{\omega}{\gamma}\right)^2 = \left[\frac{H\sin\theta\cos\left(\phi-\phi_H\right) + H_E\sin\theta\cos\phi - 4\pi M\cos 2\theta + H_K g(\delta)}{\sin^2\theta}\right]\left[\frac{H\sin\theta\cos\left(\phi-\phi_H\right) + H_E\sin\theta\cos\theta + H_K f(\delta)}{\sin^2\theta}\right] - \frac{H_K^2 p(\delta)}{\sin^2\theta} \tag{2a}$$

Here ω is the resonant frequency; γ is the magnetogyric ratio. H_K, H_σ is the uniaxial and the stress anisotropy field, respectively, and $f(\delta)$, $g(\delta)$, $p(\delta)$ as formulas of the tilt angle δ. These are revealed by

$$f(\delta) = \left(\sin^2\delta\sin^2\theta\cos 2\phi + \sin\theta\cos\theta\sin\delta\cos\delta\cos\phi\right) + \left(3/2H_K\right)H_\sigma\sin^2\theta\cos 2\phi \tag{2b}$$

$$g(\delta) = \cos 2\theta\left(\cos 2\delta + \sin^2\delta\sin^2\phi\right) + \sin 2\theta\sin 2\delta\cos\phi - \frac{3}{2H_K}H_\sigma\cos 2\theta\cos^2\phi \tag{2c}$$

$$p(\delta) = \sin^2\delta\sin^2\phi\left(\sin 2\theta\sin\delta\cos\phi + \cos 2\theta\cos\delta\right)^2. \tag{2d}$$

From Eq. (2a), the resonance field is found to be

$$H = \frac{-H_E\sin\theta\cos\phi + H_+(\delta) + \sqrt{(\omega/\gamma)^2\sin^2\theta + H_-^2(\delta) + p(\delta)H_K^2}}{\sin\theta\cos\left(\phi-\phi_H\right)} \tag{3}$$

where

$$H_\pm(\delta) = (1/2)\left[4\pi M\cos 2\theta \mp H_K\left(f(\delta) \pm g(\delta)\right)\right] \tag{4}$$

The dynamic susceptibility is found to be equal to

$$\chi = \frac{\gamma^2\left(E_{\theta\theta} + i\omega M\alpha/\gamma\right)}{\left(\omega_r - \omega^2\right) + i\omega\Delta\omega} \tag{5}$$

Writing χ as $\chi = \chi' - i\chi''$, at resonance $\omega_\gamma = \omega$, one will get imaginary part $\chi'' = \gamma^2E_{\theta\theta}/\omega\Delta\omega$ which represents the amplitude of the absorption peak.

The linewidth is an essential parameter of the ferromagnetic resonance modes, which has been widely used to account for the phenomenon of ferromagnetic resonance in many different systems. The intrinsic and the extrinsic linewidth of exchange coupled bilayer thin films have been researched. The intrinsic linewidth is a fundamental property of the magnetic material, it is related to Gilbert damping. The extrinsic linewidth is connected with magnetic inhomogeneity within the sample and the anisotropy dispersion in the thin film. For a fixed dc field-variable frequency set-up, the frequency is shown by the general formula

$$\Delta\omega = \frac{\alpha\gamma}{M}\left[E_{\theta\theta} + \frac{E_{\phi\phi}}{\sin^2\theta}\right] \tag{6}$$

Here, γ is the magnetogyric ratio, α is Gilbert damping coefficient, $E_{\theta\theta}$ is the second derivations of the energy with respect to θ, $E_{\phi\phi}$ is the second derivations of the energy with respect to ϕ.

The field linewidth is interpreted as the full width at half amplitude of the absorption curve. If one is utilizing a variable field-fixed frequency spectrometer, then the linewidth will be field linewidth and is deduced to be given by

$$\Delta H = \left(\mathrm{d}H/\mathrm{d}\omega\right)\Delta\omega \tag{7}$$

So the theoretical expression of field linewidth is obtained,

$$\Delta H = \frac{\gamma\alpha\left[E_{\theta\theta} + E_{\theta\varphi}\left(\sin^2\theta\right)^{-1}\right]}{\sqrt{3}M\left(d\omega/dH\right)}.$$

3. In-plane anisotropy case

In the present theoretical analysis, the in-plane anisotropy corresponding to $\delta = \pi/2$ of the ferromagnetic thin film is discussed. In this case, applied magnetic field H will be assumed in-plane along with the x axis and counted positive if applied magnetic field in the forward direction ($\phi_H = 0$), negative if it is in the reverse direction ($\phi_H = \pi$). As a result, $\theta = \pi/2$ will be obtained by the solution of equilibrium positions. When $H > -H_E - H_K - 3H_\sigma/2$, magnetization in the forward direction $\phi = 0$, and for $H < -H_E + H_K + 3H_\sigma/2$, it is in the reverse direction $\phi = \pi$, respectively. Note that H_E, H_K and H_σ are always considered positive.

The frequency linewidth for this in-plane anisotropy case is calculated by setting $\phi_H = 0$, $\delta = \pi/2$ and $\theta = \pi/2$. Then we can rewrite Eq. (6) as

$$\Delta\omega = \alpha\gamma\left[2\left(H + H_E\right)\cos\phi + 2H_K + 4\pi M + 3H_\sigma\right] \tag{8}$$

According to Eq. (7), the field linewidth is deduced to be equal to

$$\Delta H = 2\alpha\omega\frac{H\cos\phi + H_E\cos\phi + H_K + 2\pi M + \left(3H_\sigma/2\right)}{\cos\phi\sqrt{\omega^2 + \gamma^2(2\pi M)^2}} \tag{9}$$

Parameters used in this case $H_K = 1$ kOe, $H_E = 0.3$ kOe, $4\pi M = 6$ kG, $\gamma/2\pi = 2.8$ GHz/kOe. The variation of the frequency linewidth with applied magnetic field H in the film plane for increasing field and decreasing field is shown in Fig. 1. We find that frequency linewidth shows an increasing trend after introducing the stress field. It is seen that, as the stress anisotropy increases, the frequency linewidth for increasing field and decreasing field becomes higher and higher. The dominant contribution to the frequency linewidth is due to the fact that the stress anisotropy field changes the effective magnetic field of the system. At applied magnetic field $H = -H_E$, a higher resonance frequency is observed. It is easily found that the frequency linewidth presents as a linear combination in the decreasing and increasing fields with in-plane anisotropy field. Note that the two critical fields are not altered with stress anisotropy, i.e., $H_1 = -H_E - H_K$ and $H_2 = -H_E + H_K$. As $H_E$enhancement without H_σ, the behavior of frequency linewidth is