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Ferromagnetic Resonance in Metallic Thin Films and Thin-Film Tubes

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A model describing ferromagnetic resonance in thin-film magnetic metallic tubes is proposed and compared with the experimental ferromagnetic resonance spectra of the thin-film Ni.

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1. Introduction

Ferromagnetic resonance (FMR) is a useful method in studying thin magnetic films (Fig. 1a). Using FMR the essential parameters describing magnetic properties of thin films can be measured: the effective magnetization $4\pi M$, the

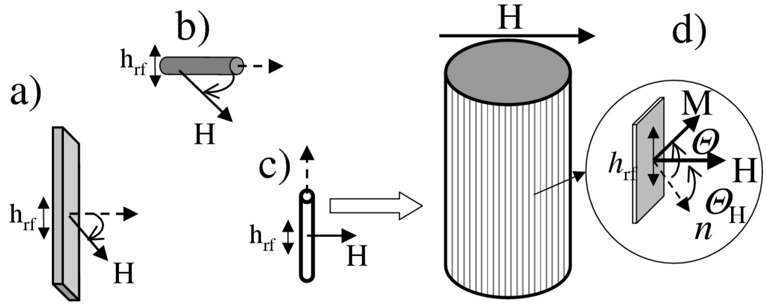

Fig. 1. Schematic drawings of the magnetic field configuration used in FMR measurements of thin films (a), magnetic wires (b), and thin-film tubes (c). Thin-film tube is divided into a large number of ribbons (d). Each ribbon is approximated by a thin film.

spectroscopic splitting factor g [1]. In magnetic wires (whiskers, amorphous wires or the arrays of nanowires) FMR has been also extensively investigated [2–4]. In "macroscopic" wires (Fig. 1b) of several μm in diameter, due to a finite skin-depth δ, the resonance field (measured in a configuration shown in Fig. 1b) is a function of the ratio a/δ, where a is the wire diameter [3] and it has been shown to increase monotonically with a/δ from $H = \omega/\gamma - 2\pi M$ — typical of non-conducting cylinder, to the in-plane resonance field of metal films: $(\omega/\gamma)^2 = H(H + 4\pi M)$. Similar results have been obtained for a system of Ni nanowire arrays [4, 5]. Definitely, less attention has been paid to FMR in thin-film tubes, in which in opposite to the wires, the thickness of the magnetic film is limited to several nm (Fig. 1c) and skin-depth effect can be neglected. In the present contribution we show a model describing FMR in thin-film tubes and we compare the model with experimental results for Ni deposited onto glass rods and and the Ni–Mn–Ga thin film tubes.

2. A model and comparison with the experiment

FMR response in metallic thin-film tubes can be described in similar way as in thin films. We apply here a configuration of the magnetic fields (Fig. 1c and d), in which h_{rf} is applied parallel to the tube axis and the static magnetic field H is applied perpendicular to it. Such a configuration has never been treated yet. Let us assume that the thin-film tube consists of many narrow thin-film ribbons as it is shown in Fig. 1d. Each ribbon is treated, in the first approximation, as a "typical" thin film with the normal n to its plane making an angle Θ_H with the field H. For the entire tube, the individual ribbons have their normals n oriented with respect to the field H in a range of $0 \leq \Theta_H \leq 2\pi$. For an individual ribbon the resonance conditions for the uniform mode are described by a standard relation [1]:

$$\left(\frac{\omega}{\gamma}\right)^2 = [H_{\mathrm{r}} \cos(\Theta - \Theta_H) - 4\pi M \cos 2(\Theta - \Theta_H)] \times \left[H_{\mathrm{r}} \cos(\Theta - \Theta_H) - 4\pi M \cos^2(\Theta - \Theta_H)\right] \quad (1)$$

with equilibrium condition $H_{\mathrm{r}} \sin(\Theta - \Theta_H) = 4\pi M \sin\Theta \cos\Theta$ for magnetization M oriented at an angle Θ with respect to normal n. $\omega = 2\pi f$ is the frequency of microwaves, γ is gyromagnetic ratio and M is the effective magnetization.

To obtain a FMR response of the entire thin-film tube, we can treat, in the first approximation, the set of our thin-film ribbons as independent in a similar way as the FMR in ferrite powders has been treated in "independent grain approach" [6]. Equation (1) is calculated for a large number of Θ_H values covering the range 0–2π and the results are historammed on a magnetic field scale. Figure 2a shows a calculated histogram which actually represents the "density" of the reduced resonance fields $h_{\mathrm{r}} = H_{\mathrm{r}}/(\omega/\gamma)$ in the range $0 \leq \Theta_H \leq 2\pi$ for infinitesimally narrow resonance line width. To simulate an experimental spectrum of a thin-film tube, the histogram f_k is convoluted with an appropriate Lorentzian broadening function $L_{j,k}$

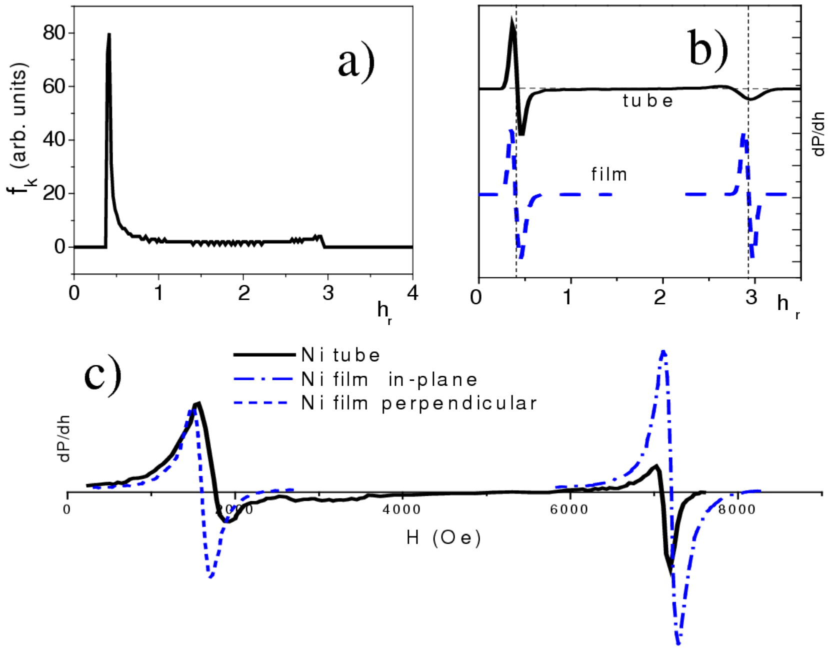

Fig. 2. (a) A histogram showing FMR pattern of a system of ribbons forming a thin-film tube. (b) Calculated first-derivative FMR spectra of a tube for finite line broadening (continuous curve) Dashed curves show the calculated spectra for a thin film. (c) Experimental spectra for a Ni thin-film tube (continuous curve) taken in the configuration shown in Fig. 1c. and for a Ni thin film (dashed curves) taken at the in-plane and perpendicular to the plane configurations, respectively.

$$L_j = \sum L_{j,k} f_k, \tag{2}$$

and the first derivative of the broadened absorption curve L_j is taken.

Figure 2b (continuous curve) shows FMR spectrum calculated for a hypothetical Ni thin-film tube ($M = 485$ Gs, $g = 2.2$) and, for a comparison, the spectra of a “normal” thin film (dashed curves) taken at $\Theta_H = 0°$ and $90°$, respectively. The most characteristic in FMR response of thin-film tubes is that the “peaks” at the shoulders are asymmetric but nearly correspond to spectra of the thin film. HH

Figure 2c shows experimental FMR spectra of a 100 nm Ni film (dashed curves) taken at in-plane ($\|$) and perpendicular to the plane ($\perp$) configurations, respectively. The resonance fields $H_{r\|} = 1310$ Oe and $H_{r\perp} = 8200$ Oe give $g = 2.21$ typical of Ni and $4\pi M = 5265$ Gs, i.e., slightly lower than 6050 Gs for pure Ni. The continuous curve in Fig. 2c shows the FMR spectrum of the thin-film Ni tube. It is seen that the the low- and high-field peaks situated on the shoulders of the spectrum approximately coincide with the Ni film’s spectra taken at the in-plane and perpendicular to the plane configurations, respectively. Hence, the

FMR results for the thin-film Ni tube are qualitatively consistent with our simple model. Such an approach has been proved useful to study magnetic properties of thin-film tubes obtained from thin Ni–Mn–Ga films after separation from the mica substrates [7]. Ni–Mn–Ga alloy exhibits large strains due to magnetic field induced rearrangement of the martensite variants [8]. This effect is diminished in thin films due to constraint of a substrate. Therefore, we were interested in the magnetic behavior of the films released from the substrates.

3. Summary

In conclusion, the FMR in thin-film metallic tubes has been qualitatively modelled in the framework of "independent ribbon" approach.

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