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The observation of non-homogeneous FMR modes in multilayer Fe/Cr structures

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Abstract

The spectrum of excitations in $[Fe/Cr]_n$ structures with a non-collinear magnetic ordering was studied by means of the FMR technique. The measurements were carried out at room temperature in the frequency range of 9.5–37 GHz with both static and microwave magnetic fields lying in the film plane. Along with the acoustic FMR mode several additional modes were observed in the longitudinal pumping configuration. The resonance spectrum of an infinite magnetic superlattice was calculated analytically on the basis of the biquadratic exchange coupling model. Both cases were considered: external magnetic field H parallel and perpendicular to the film plane. It was shown that the observed additional FMR modes correspond to the excitation of standing spin waves with wave vectors perpendicular to the superlattice plane. © 1999 Elsevier Science B.V. All rights reserved.

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The ferromagnetic, antiferromagnetic and non-collinear magnetic ordering were experimentally observed in magnetic superlattices [1–5]. Along with the usual Heisenberg-form energy term, the so-called "biquadratic" one $J_2(\boldsymbol{M}_1\boldsymbol{M}_2)^2$ should be taken into account to explain this non-collinear ordering [2]. In spite of numerous experimental evidences and theoretical considerations, the origin of J_2 is not clear yet.

In this work we use the ferromagnetic resonance (FMR) technique and static magnetization measurements to investigate the $[Fe/Cr]_n$ multilayers with a non-collinear magnetic ordering. The results of static and resonance experiments are discussed in the framework of the biquadratic exchange coupling model. The FMR technique was widely used by several experimental groups (see overview in Ref. [6]) for investigation of magnetic superlattices, but only a few works included the biquadratic coupling into the analysis of the obtained results [7–9].

We used two samples: S9 – $[Cr(10.4\,Å)/Fe(21.2\,Å)]_{12}$ and S14 – $[Cr(7.7\,Å)/Fe(33.2\,Å)]_{16}$ epitaxially grown on the MgO substrate. The crystallographic plane (1 0 0) of Fe layers was parallel to the sample plane.

The magnetization measurements were performed on a vibrating sample magnetometer in two orientations of the applied magnetic field: H parallel (up to 17 kOe) and H perpendicular to the film plane (up to 9 kOe). The in-plane magnetization curves demonstrated a large value of residual magnetic moment typical for systems with non-collinear magnetic ordering. The corresponding angles of neighboring magnetic layers ordering were 145° for sample S9 and 110° for sample S14 (see details in Ref. [10]).

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The FMR measurements were performed in the 9.5–37 GHz frequency range with both static $\boldsymbol{H}$ and microwave $\boldsymbol{h}$ magnetic fields lying in the film plane. The setup configuration allowed to employ both the transverse ($\boldsymbol{h}\perp\boldsymbol{H}$) and the longitudinal ($\boldsymbol{h}\|\boldsymbol{H}$) FMR excitation. In the case of transverse pumping we observed one very strong absorption line which corresponded to the homogeneous precession of all iron magnetic moments (acoustic mode). In the case of longitudinal pumping several other less intensive modes were observed. The results of FMR experiments for two samples are presented in Fig. 1 by open (acoustic branch) and solid points.

To explain the origin of several FMR modes observed in the longitudinal pumping configuration, we carried out an analytical calculation of infinite superlattice resonance spectra in the framework of the biquadratic exchange coupling model. Supposing that the magnetic moment of every iron layer oscillates as a single vector, we can write the magnetic energy per unit surface area as follows:

$$E = -d\sum_{i=1}^{n}(\boldsymbol{M}_i\boldsymbol{H}) + \frac{J_1}{M_S^2}\sum_{i=1}^{n-1}(\boldsymbol{M}_i\boldsymbol{M}_{i+1}) + \frac{J_2}{M_S^4}\sum_{i=1}^{n-1}(\boldsymbol{M}_i\boldsymbol{M}_{i+1})^2 + d\frac{K_{\text{eff}}}{2}\sum_{i=1}^{n}(\boldsymbol{M}_i\boldsymbol{z})^2, \quad (1)$$

where J_1 and J_2 are the bilinear and biquadratic interlayer coupling constants. $\boldsymbol{M}_i$ is the magnetization of the ith iron layer, d the iron layers thickness, K_{eff} the effective surface anisotropy factor and $\boldsymbol{z}$ the unit normal vector to the film plane. We ignored the fourfold in-plane anisotropy in our calculations as its usual value (about 500 Oe [8,9]) is much less than the interlayer exchange fields (about 10 KOe) in our samples. The following calculations will be performed separately for two cases: $\boldsymbol{H}$ parallel and $\boldsymbol{H}$ perpendicular to the film plane.

(a) ***H** parallel to the film plane.* The minimization of energy (1) gives the equilibrium angles between the external magnetic field direction and $\boldsymbol{M}_i$:

$$\alpha_i = (-1)^i\arccos(M/M_S), \quad (2)$$

where M is the projection of the iron layers magnetization on the field direction, which can be defined as an implicit function of H:

$$H = AM + BM^3 \quad \text{for} \quad H \leqslant H_S$$

$$M = M_s \quad \text{for} \quad H > H_S. \quad (3)$$

Here $A = (4J_1 - 8J_2)/dM_S^2$, $B = 16J_2/dM_S^4$, $H_S = (4J_1 + 8J_2)/dM_S$ is the saturation field in the parallel configuration. The usual Landau–Lifshitz equations without the dissipation term are used to find the resonance spectrum of the system:

$$\gamma^{-1}\dot{\boldsymbol{M}}_i = -[\boldsymbol{M}_i\boldsymbol{H}_i^{\text{eff}}],$$

$$\text{where } H_i^{\text{eff}} = -(\partial E/\partial \boldsymbol{M}_i)d^{-1}. \quad (4)$$

After linearization of Eq. (4) near the equilibrium position (2, 3), the solution can be found in the form of a spin wave propagating along the film plane normal. The oscillation frequency ω_q is determined by the constant precession phase shift q between the neighboring magnetic layers. Omitting the intermediate calculations, we are giving only the final expressions for ω_q:

$$\left(\frac{\omega_q}{\gamma}\right)^2 = [C(1+\cos q) + K_{\text{eff}}]\,[CM^2(1+\cos q) + (C + BM^2)(M_S^2 - M^2)(1-\cos q)]$$

for $H \leqslant H_S$,

$$\left(\frac{\omega_q}{\gamma}\right)^2 = \left(H - H_S\frac{1-\cos q}{2}\right)\times\left(H - H_S\frac{1-\cos q}{2} + K_{\text{eff}}M_S\right)$$

for $H > H_S$. (5)

where $C = (A + BM^2)/2$.

(b) ***H** perpendicular to the film plane.* A similar procedure for the perpendicular case gives the following

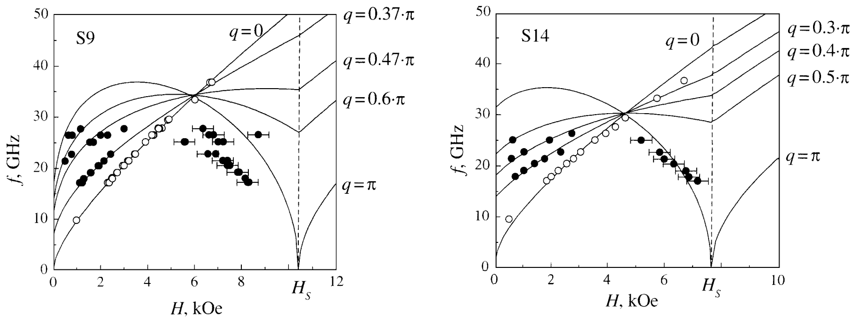

Fig. 1. Experimental and theoretical FMR spectra for two samples. $\boldsymbol{H}$ is parallel to the film plane.

expressions for magnetization in the field direction:

$$M = H/K_{\text{eff}} \quad \text{for} \quad H \leqslant K_{\text{eff}}\, M_0,$$

$$H = (A + K_{\text{eff}})M + BM^3$$

$$\text{for} \quad K_{\text{eff}}\, M_0 < H < H_S + K_{\text{eff}} M_S,$$

$$M = M_S \quad \text{for} \quad H \geqslant H_S + K_{\text{eff}}\, M_s. \tag{6}$$

The frequencies ω_q for this orientation of magnetic field are given by the formula

$$\left(\frac{\omega_q}{\gamma}\right)^2 = K_{\text{eff}} B\,(M_S^2 - M_0^2) \times \left(M_0^2 - \frac{H^2}{K_{\text{eff}}^2}\right)(1 - \cos q)$$

$$\text{for} \quad H \leqslant K_{\text{eff}}\, M_0,$$

$$\left(\frac{\omega_q}{\gamma}\right)^2 = C(1 + \cos q)\,[CM^2(1 + \cos q)$$

$$+ [K_{\text{eff}} + (C + BM^2)(1 - \cos q)]\,(M_S^2 - M^2)]$$

$$\text{for} \quad K_{\text{eff}} M_0 < H < H_S + K_{\text{eff}}\, M_S,$$

$$\left(\frac{\omega_q}{\gamma}\right) = H - K_{\text{eff}} M_S - H_S \frac{1 - \cos q}{2}$$

$$\text{for} \quad H \geqslant H_S + K_{\text{eff}} M_S. \tag{7}$$

For $q = 0$, Eqs. (5) and (7) give the frequency of the acoustic, and for $q = \pi$ – of the optical branches of FMR spectra, which coincide with the result, obtained in [7]. Supposing $H = 0$ in Eqs. (5) and (7) we come to the spectrum obtained in Ref. [11] in the absence of the external field.

The values of J_1, J_2, M_S and K_{eff}, derived from the approximation of experimental magnetization curves with expressions (3) and (6) are the following:

$J_1 = 0.40$ erg/cm^2, $J_2 = 0.23$ erg/cm^2,

$M_S = 1.62 \times 10^3$ emu/cm^3,

$K_{\text{eff}} = 11$ – for sample S9;

$J_1 = 0.22$ erg/cm^2, $J_2 = 0.39$ erg/cm^2,

$M_S = 1.59 \times 10^3$ emu/cm^3,

$K_{\text{eff}} = 13$ – for sample S14.

These values of magnetic constants were used to calculate the theoretical spectra according to formulas (5) and (7) (lines in Figs. 1 and 2). The figures show the acoustic ($q = 0$), the optical ($q = \pi$) and several modes with intermediate q values. The results of the calculation, in which only the static data were used, exhibit a reasonable agreement with available experimental resonance data, a qualitative one for sample S9, and a quantitative one for S14. It allows us to affirm that a series of standing spin waves with wave vectors perpendicular to the film plane was excited in our experiments.

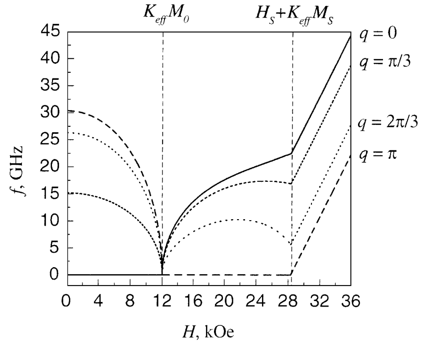

Fig. 2. Calculated spectra for sample S14. ***H*** is perpendicular to the film plane.

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