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Temperature dependence of interlayer coupling in Fe/Cr superlattices — FMR studies

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Abstract

The ferromagnetic resonance in a $[\mathrm{Fe}(30\,\text{Å})/\mathrm{Cr}(10\,\text{Å})]_{10}$ superlattice with a relatively large value of biquadratic coupling constant was studied in a temperature range from 400 K down to liquid-nitrogen temperature. The monocrystalline sample was grown by means of the MBE technique on a MgO [1 0 0] substrate. Measurements were performed in magnetic fields up to 10 kOe at frequencies ranging from 17 to 37 GHz under both transversal and longitudinal FMR excitations. Resonance spectra with several modes including the acoustic and the optical branches were observed in the whole temperature range. Temperature dependence of both bilinear and biquadratic coupling constants was derived from the experimental spectra. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Multilayers—metallic; Exchange coupling—biquadratic; Ferromagnetic resonance

Among all magnetic multilayers the Fe/Cr/Fe system is one of the most extensively investigated [1]. The biquadratic interlayer coupling, first observed in Refs. [2,3], also increased the common interest to the problem of magnetic interaction of two ferromagnetic layers through a chromium spacer. Nevertheless, the origin of the biquadratic and even the bilinear coupling in Fe/Cr/Fe structures is still not clear. The temperature dependence of interlayer interaction is investigated mostly for relatively large (>30 Å) spacer thickness, where the coupling mechanism can be different from that through a thin Cr layer and is known to be due to the spin density wave in chromium [1,4].

The $[\mathrm{Fe}(30\,\text{Å})/\mathrm{Cr}(10\,\text{Å})]_{10}$ superlattice used in our experiments was prepared by means of the MBE technique on a MgO [1 0 0] substrate. A 10 Å iron seed layer and 1000 Å silver buffer layer were deposited at 130°C onto the substrate before growing the superlattice. The superlattice itself was deposited at 150°C and, according to the results of low-energy electron diffraction, demonstrated a well-defined monocrystalline structure with [1 0 0] axis perpendicular to the sample plane.

FMR measurements were performed using a homemade spectrometer at frequencies ranging from 17 to 37 GHz in magnetic fields up to 10 kOe applied in the sample plane. Due to a radial direction of microwave magnetic field on the bottom of a cylindrical resonator, both the transversal and the longitudinal FMR pumping was imposed on the sample during our measurements. The experimental setup allowed us to vary the sample temperature from 80 to 400 K. We observed multiple absorption lines including the optical and the acoustic resonance branches at all investigated temperatures (for detailed discussion of these modes see Refs. [5,6]). Two experimental spectra obtained at room and at liquid-nitrogen temperature are shown in Fig. 1. The observed spectra, especially the optical branch, show a strong temperature dependence. At nitrogen temperature the resonance fields for two FMR branches in the strong magnetic field part of the plot (shown by dark squares and dark triangles) increased by almost 2 kOe with respect to their room temperature position. To derive the

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interlayer coupling parameters from the measured spectra, we performed computer simulations of the superlattice resonance spectrum on the basis of the biquadratic coupling model, taking into account the fourfold in-plane magnetic anisotropy of iron and the real number of magnetic layers in the system. The following energy expression was used to describe the magnetic properties of the multilayer:

$$
\begin{aligned}
E = & -d\sum_{j=1}^{n}(\mathbf{H}\cdot\mathbf{M}_j) - \frac{J_1}{M_S^2}\sum_{j=1}^{n-1}(\mathbf{M}_j\cdot\mathbf{M}_{j+1}) \\
& - \frac{J_2}{M_S^4}\sum_{j=1}^{n-1}(\mathbf{M}_j\cdot\mathbf{M}_{j+1})^2 + d\frac{K_{\mathrm{eff}}}{2}\sum_{j=1}^{n}(\mathbf{M}_j\cdot z)^2 \qquad (1) \\
& - d\frac{H_a}{4M_S^3}\sum_{j=1}^{n}[(\mathbf{M}_j\cdot x)^4 + (\mathbf{M}_j\cdot y)^4 + (\mathbf{M}_j\cdot z)^4],
\end{aligned}
$$

where J_1 and J_2 are the bilinear and biquadratic coupling constants, $\boldsymbol{M}_j$ is the magnetization vector of the jth iron layer, d is the thickness of each iron layer, K_{eff} is the effective surface anisotropy coefficient, which includes the demagnetization field and the surface anisotropy, H_a is the effective fourfold anisotropy field with easy axes x, y and z, where the z-axis is normal to the sample plane, and n is the number of ferromagnetic layers in the structure. The detailed description of these calculations can be found in Ref. [6].

The calculated spectra are shown in Fig. 1 by solid lines. The J_1 and J_2 values were chosen to provide the best fit to the acoustic (dark circles) and optical (dark squares) branches of the experimental spectra. M_S value was taken to be equal to that in bulk iron. The fourfold anisotropy field H_a was chosen to describe the difference in experimental spectra with magnetic field applied along the hard and easy anisotropy axes in the sample plane. It was proved to be equal to 500 Oe, which coincided with the bulk value, and did not exhibit any change in temperature. The temperature dependencies of J_1, J_2 and saturation field H_S are shown in Fig. 2. The confidence bands presented in the figure correspond to parameter values that give a one linewidth deviation of calculated curves from the experimental data. Taking into account this uncertainty in parameter definition, we can affirm that both the bilinear J_1 and the biquadratic J_2 coupling constants increase significantly with cooling the sample down to 80 K. The observed J_1, J_2 and H_S temperature dependencies can be treated as linear within our precision. The presented results for J_1 are in quantitative agreement with the data from Ref. [7], where temperature dependencies of J_1 and J_2 were derived from FRM measurements for a Fe(40 Å)/Cr(11 Å)/Fe(40 Å) sandwich. Our J_2 values are about 3 times larger, than that reported in Ref. [7], which can be easily ascribed to the difference in the interfaces morphology. It is worth noting that an absolutely different H_S on temperature dependence was reported in Ref. [8] for a significantly larger chromium thickness (80 and 102 Å). It shows that different coupling mechanisms can be responsible for interlayer exchange in the cases of thick and thin chromium spacers.

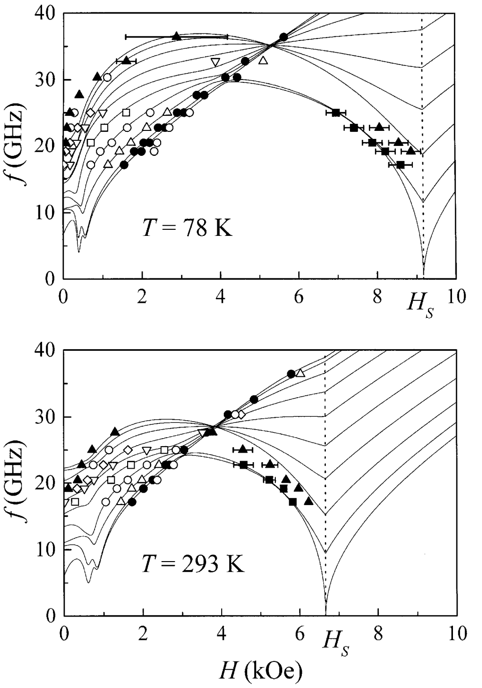

Fig. 1. FMR spectra for a [Fe(30 Å)/Cr(10 Å)]$_{10}$ superlattice at two different temperatures with magnetic field applied along the hard magnetization axis of iron in the film plane. Points — experimental data, solid curves — results of numerical simulation (see in text). Error bars represent the observed line width when it exceeds the point size.

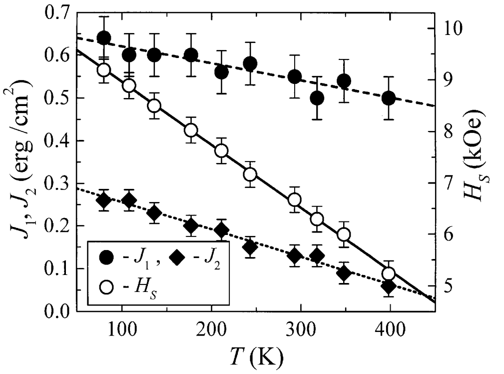

Fig. 2. Temperature dependence of saturation field H_S and coupling constants J_1 and J_2. The lines are guides to the eye.

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