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Spin Wave Resonance in the $[(Co_{0.88}Fe_{0.12})/Cu]_N$ Synthetic Antiferromagnet

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Abstract—The $[(Co_{0.88}Fe_{0.12})/Cu]_N$ synthetic antiferromagnet has been investigated by the spin wave resonance method over the entire range of angles of an external dc magnetic field to the film surface normal. The investigations have shown that the superlattice under study consists of two exchange-coupled magnetic subsystems, each manifested in the recorded spectra as a series of spin-wave modes. The dependence of the linear region of propagation of a standing spin-wave mode on the sample orientation in an external magnetic field has been established.

Keywords: spin wave resonance, synthetic antiferromagnet, exchange coupling constant.

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The $[Co_{1-x}Fe_x/Cu]_N$ superlattices exhibit a unique combination of magnetic properties, which makes it possible to use them in magnetic sensors with record performances [1–3]. The results of study of the microwave giant magnetoresistive effect (μGMR) [1–3] showed the efficiency of the electrodynamic techniques in the centimeter wavelength range for describing the electromagnetic properties of superlattices.

The methods conventionally used to measure the dynamic characteristics of magnetic systems are ferromagnetic resonance (FMR) and spin wave resonance (SWR) [4–6]. The angular dependences of the SWR and FMR spectra allow one to determine the parameters of a magnetic system, including effective magnetization M_{eff}, exchange coupling constant A, the orthogonal and in-plane anisotropy constants, and the surface anisotropy constant.

The results of theoretical [7, 8] and experimental [9, 10] studies of the dynamic characteristics of multilayers demonstrate the dependence of the spectrum shape on both the structural (thickness and number of layers) and magnetic (magnetization and anisotropy field) parameters of a separate layer [11]. Thus, the FMR and SWR methods make it possible to establish the integral magnetic parameters of the planar [CoFe/Cu] superlattice and estimate their interplay with other effects observed on these composites [12].

The dynamic properties of the $[(Co_{0.88}Fe_{0.12})/Cu]_N$ superlattice with a nonmagnetic spacer thickness of $t_s = 0.95$ nm were examined. The sample was synthesized by magnetron sputtering on an MPS-4000-C6 setup [13]. Corning glass was used as a substrate material. The sample was a planar nanostructure with the $Ta(5\ nm)/Ni_{48}Fe_{12}Cr_{40}(5\ nm)/[Co_{88}Fe_{12}(1.5\ nm)/Cu(0.95\ nm)]_{24}/Ta(5\ nm)$ composition.

X-ray study on a DRON-3M diffractometer (CoK_α radiation) showed that the superlattice has an ideal layer structure with an fcc lattice and a $\langle 111 \rangle$ axial texture with the axis normal to the layer plane. The microwave GMR measurement results for the structure under study were reported in [3]. According to the $M(H)$ dependences measured on similar structures [13], the saturation field takes the values in the range of 200–300 Oe at different buffer layer compositions.

The microwave spectra of the films were measured at room temperature in the X-band (the resonator pumping frequency was $f = 9.47$ GHz) on a Bruker ELEXSYS E580 spectrometer (Germany), Krasnoyarsk Territorial Center for Collective Use, Krasnoyarsk Scientific Center, Siberian Branch, Russian Academy of Sciences; the sample was placed in the antinode of an ac magnetic field $h_\sim$ of a transmission resonator. The dc magnetic field $\mathbf{H}$ was varied both in the film plane in angle φ and in the plane parallel to the film normal at different angles θ counted from the film plane normal.

The dependence of the positions of resonance fields H_n on wave vector k related to the mode

Table 1. Magnetic parameters

Magnetic parameters		Subsystem 1	Subsystem 2
FMR resonance fields	$\theta = 90°$	$H^{\parallel}_{0\,\mathrm{low}} = 840$ Oe	$H^{\parallel}_{0\,\mathrm{high}} = 1550$ Oe
	$\theta = 0°$	$H^{\perp}_{0\,\mathrm{low}} = 8700$ Oe	$H^{\perp}_{0\,\mathrm{high}} = 15100$ Oe
Saturation magnetization		$M_{S\,\mathrm{low}} = 870$ G	$M_{S\,\mathrm{high}} = 939$ G
Uniaxial crystalline anisotropy field		$H_{u\,\mathrm{low}} \approx 3$ Oe	$H_{u\,\mathrm{high}} \cong -730$ Oe

number n as $k = n\pi/d$ (d is the film thickness; and $n = 1, 3, 5, \ldots$, for bulk spin modes; and $n = 0$ for a homogeneous FMR mode) at $\theta = 90°$ has the form [14]

$$H_n = \left\{\left[\left(\frac{\omega}{\gamma}\right)^2 + (2\pi M_{\mathrm{eff}})^2\right]^{1/2} - 2\pi M_{\mathrm{eff}}\right\} - \eta_{\mathrm{eff}} k_n^2. \quad (1)$$

The positions of resonance fields H_n at $\theta = 0°$ are determined as

$$H_n = \frac{\omega}{\gamma} + 4\pi M_{\mathrm{eff}} - \eta_{\mathrm{eff}} k_n^2, \quad (2)$$

where $\omega = 2\pi f$ is the cyclic frequency, s^{-1}; $\gamma = 1.758 \times 10^7$ Hz/Oe, is the gyromagnetic ratio; $n_{\mathrm{eff}} = 2A/M_s$ is the spin-wave stiffness, Oe cm^2, related to the exchange coupling constant A, erg/cm; and M_S is the saturation magnetization.

Regardless of the geometry of the SWR experiment ($\theta = 0°$ or $90°$), the effective exchange stiffness in the field coordinates is calculated using the formula

$$\tilde{\eta}_{\mathrm{eff}} = \frac{H_1 - H_n}{n^2 - 1}. \quad (3)$$

The anisotropy contribution can be estimated from the FMR equations for magnetically anisotropic materials obtained in the effective field approximation [15]

$$\frac{\omega}{\gamma} = [(H + H_{\mathrm{eff}})(H + H_u)]^{1/2} \quad (4)$$

at $\theta = 90°$ and

$$\frac{\omega}{\gamma} = [(H - H_{\mathrm{eff}})(H - H_{\mathrm{eff}} - H_u)]^{1/2} \quad (5)$$

at $\theta = 0°$.

Here, $H_{\mathrm{eff}} = 4\pi M_S + H_K$ is the effective field that takes into account the effect of elastic stresses and H_u is the uniaxial anisotropy field.

The microwave absorption curves for the $[CoFe/Cu]_N$ synthetic antiferromagnet in the field oriented in the film plane ($\theta = 90°$) demonstrate a complex spectrum with the invariable structure (the same resonance fields and linewidths of spectral components) over the entire range of angles φ, which is indicative of the isotropy of the magnetic parameters in the film plane. When external dc magnetic field H changes relative to the film plane normal, the microwave absorption curves have a form of a complex spectrum over the entire range of angles θ (Figs. 1a, 1b). The experimental microwave spectra were decomposed into components using the differentiated Lorentzian functions (see the example in Figs. 1c, 1d).

The analysis of the spectra allows us to draw the following conclusions. Over the entire measuring angle range, both the bulk standing spin-wave modes and the surface ones are excited in the film. The microwave spectrum at any angle θ consists of two portions: low-field and high-field. The presence of two portions in the SWR spectra described by separate series of bulk standing spin-wave modes gives us grounds to consider the superlattice as two magnetic subsystems with different magnetic parameters. The ability of the FMR and SWR methods to detect the two-phase character was demonstrated in [14, 16].

The approximation of the experimental $H_n(n^2)$ dependences at $\theta = 90°$ and $0°$ (Fig. 2) allows one to determine the FMR resonance fields ($n = 0$), and Eqs. (4) and (5) make it possible to estimate M_S and H_u for each subsystem (see Table 1).

Using Eq. (3) and the $H_n(n^2)$ dependences (Fig. 2), we calculated the effective exchange stiffness and found $\tilde{\eta}_{\mathrm{eff}}$: $\tilde{\eta}^{\perp}_{\mathrm{eff}} \approx 80$ Oe for both subsystems at $\theta = 0°$ and $\tilde{\eta}^{\parallel}_{\mathrm{eff}} \approx 20$ Oe for both subsystems at $\theta = 90°$. At the same time, it is well-known that the experimental n_{eff} values in both geometries in the homogeneous films are equal [14]. The difference between the experimental $\tilde{\eta}_{\mathrm{eff}}$ values can be explained by the change in the linear size of the planar region in which a standing spin-wave mode is excited, i.e., a certain effective thickness d^i_{eff} of the subsystem. The latter indicates that, at $\theta = 0°$ and $90°$, the effective pinning of the exchange spin wave occurs inside the film, but at different thicknesses d^i_{eff}. Poimanov et al. [17] discussed the possibility of the formation of nodes of an exchange spin wave inside a multilayer film by the internal boundary conditions, rather than the conventional Kittel boundary conditions on the outer film surfaces. The features of the SWR spectra in bilayer films caused by the displacement of the standing spin

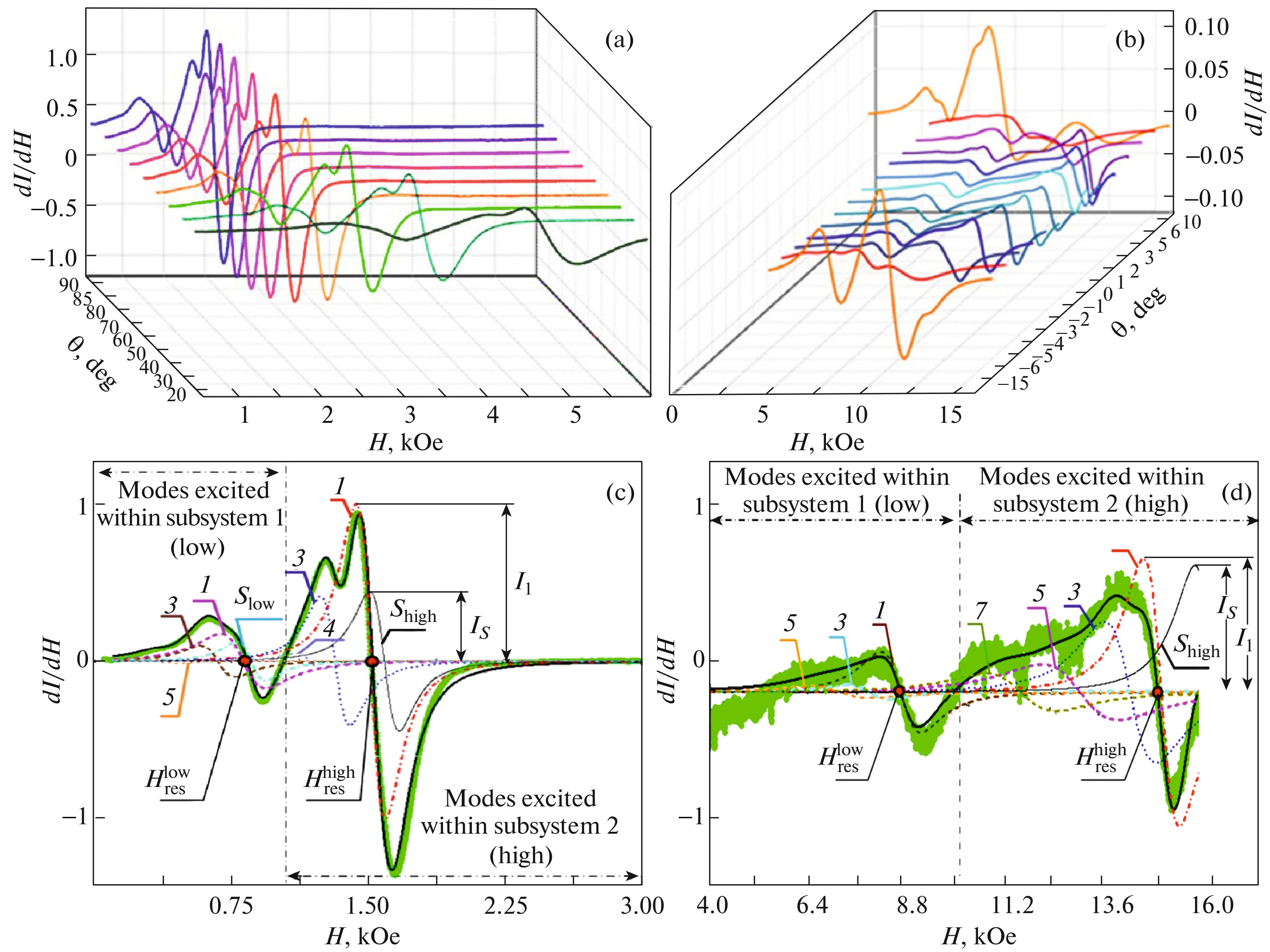

Fig. 1. Evolution of the spectra in the angle range (a) from 90° to 20° and from (b) 10° to −15° and example of decomposition of the experimental spectra at (c) θ = 90° and (d) 0°. Character *S* denotes the surface modes and *I* denotes the intensities of the surface and first bulk modes. Lines in (c) and (d) denoted by Arabic numerals indicate bulk standing spin-wave modes.

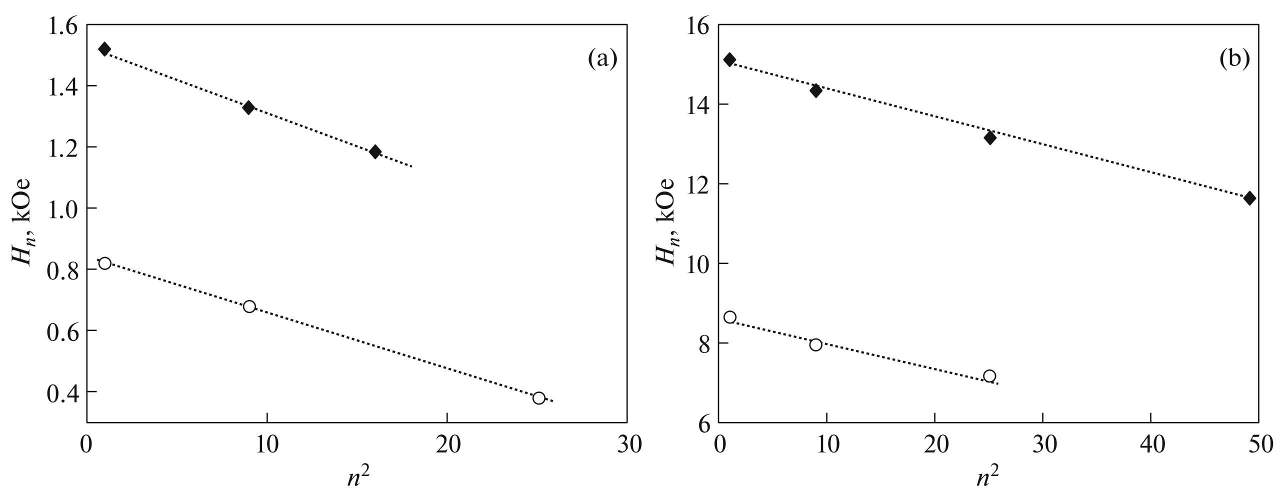

Fig. 2. Experimental $H_n(n^2)$ dispersion dependences for θ = (a) 90° and (b) 0°. Rhombs mark the values for the strong-field spectral portion; circles mark the values for the weak-field one.

wave node from the interface were detected in [18]. We assume that the d^i_{eff} values in different geometries differ by a factor of 2, which follows from the experimental relation $(\tilde{\eta}^{\perp}_{eff}/\tilde{\eta}^{\parallel}_{eff}) = 4$ (see additional materials in the online version of the article).

Assuming $d^i_{eff} = 58.8$ nm at $\theta = 90°$ and using saturation magnetization $M_{S\ high}$ from Table 1 and Eq. (3), we obtain the effective exchange coupling constant $A_{eff} \sim 0.4 \times 10^{-7}$ erg/cm. Note that the estimated A_{eff} value for the fcc-Co films (200 nm) is 1.3×10^{-6} erg/cm [10]; with a decrease in the Co thickness, the A_{eff} value can decrease by an order of magnitude [19]. The great difference between the A_{eff} value for the multilayers with an ultrathin (~1.5 nm) CoFe layer at a nonmagnetic Cu spacer thickness of ~0.95 nm and the analogous parameter of the single-layer films is explained by the integral contribution of partial exchange interactions of individual ferromagnetic layers and partial exchange between ferromagnetic layers through a nonmagnetic spacer to this parameter.

The $[(Co_{0.88}Fe_{0.12})/Cu]_N$ superlattice with a thickness of ~60 nm, in contrast to the similar system with a thickness of ~30 nm, consists of two exchange-coupled magnetic subsystems, which manifest themselves as two sets of exchange standing spin-wave modes in the SWR spectrum over the entire range of angle θ. The uniaxial perpendicular anisotropy constants of the subsystems have different signs and values. The change in the linear region of propagation of an exchange spin wave in a superlattice depending on the film orientation in an external dc magnetic field was found. The established features of the magnetic system can be used to control the GMR value during superlattice synthesis.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

SUPPLEMENTARY MATERIALS

Supplementary materials are available for this article at https://doi.org/10.1134/S1063785020110140 and are accessible for authorized user.

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