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Spin-Wave Resonance in Co/Pd Magnetic Multilayers and NiFe/Cu/NiFe Three-Layered Films

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The spectrum of standing spin waves has been detected by the ferromagnetic resonance method in NiFe(740 Å)/Cu/NiFe(740 Å) three-layered film structure in the perpendicular configuration for the copper thickness $d_{\mathrm{Cu}} \leq 30$ Å. At thicknesses $d_{\mathrm{Cu}} > 30$ Å, the resonance absorption curve is a superposition of two spin-wave resonance spectra from individual ferromagnetic NiFe layers. For Co/Pd multilayer films, united spin-wave resonance spectra have also been observed at thicknesses of the paramagnetic palladium layer up to $d_{\mathrm{Pd}} < 30$ Å. The partial exchange stiffness has been calculated for a spin wave propagating across the Pd layer ($A_{\mathrm{Pd}} = 0.1 \times 10^{-6}$ erg/cm). This value is always positive (up to the critical thickness of the palladium interlayer $d_{\mathrm{Pd}} < d_{\mathrm{c}}$) or equal to zero ($d_{\mathrm{Pd}} > d_{\mathrm{c}}$).

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Magnetic nanostructures represent a modern object of investigations in condensed-matter physics and materials science and pose a number of important questions and problems before researchers. One of them is an understanding of the mechanism of coupling between nanostructured components. In particular, it is the interlayer interaction of ferromagnetic layers through intermediate nonmagnetic layers that in many instances determines various physical properties of this class of materials. Therefore, a great number of experimental and theoretical works have been devoted to studying the nature of interlayer interaction in these nanosystems [1]. This interest was stimulated by the discovery of effects in these systems that had a great applied importance, in particular, the giant magnetoresistance (GMR) effect. It is generally accepted that the GMR effect (and a number of others) in multilayer films is due to oscillating interlayer exchange coupling of ferromagnetic layers through nonmagnetic intermediate layers; ferromagnetic layers in this case can be exchange-coupled in a ferromagnetic or antiferromagnetic way, depending on the thickness of the nonmagnetic layer [2]. The oscillation period, the sign of the interlayer exchange coupling, and its strength are determined from an analysis of hysteresis loops [3, 4], which is associated with a great variety of procedures that allow a hysteresis loop to be measured. (A comprehensive analysis of the effects of coupling of ferromagnetic layers through nonmagnetic layers in multilayer films is given in [5].)

One of the methods for studying effects of interlayer exchange coupling in multilayer systems is the ferromagnetic resonance (FMR) method [6]. In this case, a special geometry of FMR is used at which the constant magnetic field lies in the film plane (parallel configuration).

The magnetic field direction perpendicular to the film plane (perpendicular configuration), as a rule, is not used in multilayer systems. Note that, in ferromagnetic films, as well as in multilayer ferromagnet/ferromagnet films, it is experiments in the perpendicular configuration that are considered most informative: they allow the spectrum of exchange standing spin waves (SWR) to be measured and the exchange coupling constant inside the ferromagnetic layer and the bulk and surface anisotropy constants to be determined experimentally (see, for example, [3]). At the same time, when measuring FMR in the perpendicular configuration of multilayer films ferromagnet/nonmagnetic noble or transition metal (Pd, Cu, etc.), an experimenter faces the following situations: the FMR line broadens and disappears [7], a broad inhomogeneous FMR line is observed [8], or several resonance lines are observed [8–10]. In the last case, the elucidation of the nature of additional modes requires separate investigations. The goal of our investigation is to demonstrate that these additional modes in Co/Pd multilayer films and in NiFe/Cu/NiFe three-layered films at certain thicknesses of the nonmagnetic metal represent spin-wave resonance modes.

PROCEDURE AND EXPERIMENTAL RESULTS

Studies of FMR in the perpendicular configuration were performed using a standard *x*-band spectrometer with the pump cavity frequency $f = 9.2$ GHz at room temperature with samples of two types.

A NiFe/Cu/NiFe polycrystalline three-layered structure was obtained by the thermal evaporation method as follows. The first NiFe layer of the permalloy composition was sputtered onto a glass substrate in a plane-parallel magnetic field (~50 Oe) to induce a uniaxial anisotropy in the ferromagnetic film. An interlayer of diamagnetic copper was formed in the wedge form with a maximum thickness of ~50 Å by slowly moving the shutter in the process of sputtering. Next, the second NiFe layer was sputtered similarly to the first one. The thickness of an individual ferromagnetic layer in the three-layered structure was 740 Å, and the thickness of the diamagnetic Cu interlayer made in the wedge form varied from 0 to 50 Å with a gradient of 0.93 Å/mm.

Co/Pd multilayer films with paramagnetic palladium layers were obtained by chemical deposition from aqueous solutions of salts of the corresponding metals onto glass. In a series of Co/Pd samples (20 samples in all), the thicknesses of both the ferromagnetic Co layer (from 30 to 260 Å) and the nonmagnetic intermediate Pd layer (from 9 to 50 Å) were varied. The Co layers had an fcc structure because of the introduction of 6 at % phosphorus (P) into the Co deposit [11].[1]

Up to five well-identified resonance-absorption peaks were observed in the microwave absorption spectra measured for a NiFe/Cu(XÅ)/NiFe three-layered system up to the diamagnetic interlayer thickness $d_{\text{Cu}} <$ 30 Å (a typical resonance absorption curve for a NiFe/Cu/NiFe sample with $d_{\text{Cu}} = 13$ Å is shown in Fig. 1). It is seen that the main peak intensity substantially exceeds the intensities of additional peaks.

The resonance absorption curve for the NiFe/Cu/NiFe three-layered structure with $d_{\text{Cu}} > 30$ Å represented a superposition of two spectra from individual NiFe ferromagnetic layers (Fig. 2 presents the absorption curve for the NiFe(740 Å)/Cu(42 Å)/NiFe(740 Å) sample, in which the doublets of the main peak and additional modes are clearly defined).

From seven to five resonance modes were also observed in the microwave absorption curves measured for films of the Co/Pd series in the orthogonal orientation in the external magnetic field (see the inset in Fig. 3) under the condition that the palladium layer thickness $d_{\text{Pd}} \leq 30$ Å (15 samples). At large layer thicknesses ($d_{\text{Pd}} > 30$ Å), the microwave absorption curve represented a single broad FMR peak.

An analysis of the angular dependence of the observed spectra, an analysis of the dependences of the

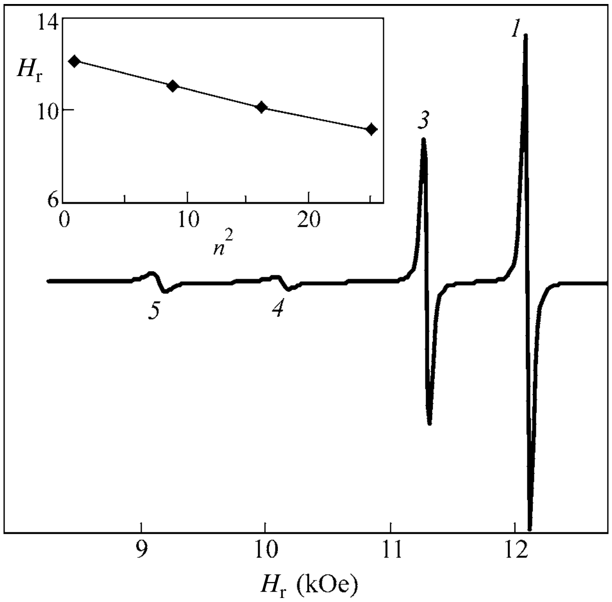

Fig. 1. Typical resonance absorption curve in the perpendicular configuration of the experiment on NiFe/Cu($d_{\text{Cu}} \leq 30$ Å)/NiFe three-layered structure. The inset shows the resonance field H_r vs. the square of the mode number in the microwave spectrum n^2 for the NiFe(740 Å)/Cu(13 Å)/NiFe(740 Å) sample.

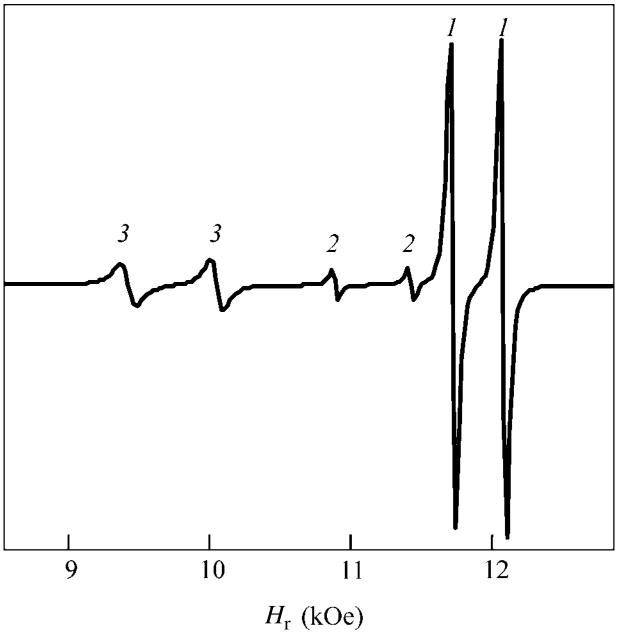

Fig. 2. Typical resonance absorption curve in the perpendicular configuration of the experiment on NiFe/Cu($d_{\text{Cu}} >$ 30 Å)/NiFe three-layered structures.

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[1] The specific features of the structure and magnetic properties of these Co/Pd films are also reported in [12].

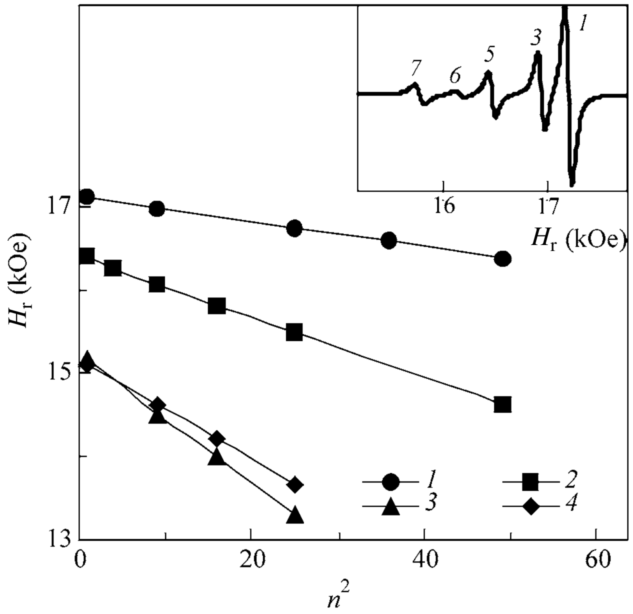

Fig. 3. Resonance field in the perpendicular configuration of the experiment for Co/Pd multilayers vs. the square of the mode number in the microwave spectrum for (*1*) [Co(200 Å)/Pd(10 Å)] · 12, (*2*) [Co(100 Å)/Pd(10 Å)] · 11, (*3*) [Co(50 Å)/Pd(14 Å)] · 7, and (*4*) [Co(100 Å)/Pd(30 Å)] · 25. The inset shows the form of the resonance absorption curve for the [Co(200 Å)/Pd(10 Å)] · 12 sample.

intensities of the main and additional peaks, and the observed order of their arrangement all indicate that the microwave spectrum in these films represents spin-wave modes of standing exchange spin waves; that is, we observed a spin-wave resonance in these systems.

An analysis of the presented microwave spectra (Figs. 1, 3) allows the conclusion that a surface spin pinning close to the Kittel surface pinning model is accomplished in this case: the intensities of the odd peaks exceed the intensities of the even peaks. The resonance fields of these spin-wave modes are described by the standard Kittel equation

$$\left(\frac{\omega}{\gamma}\right) = H - 4\pi M_{\text{eff}} + \frac{2A_{\text{eff}}}{\langle M\rangle}\left(\frac{n\pi}{d}\right)^2, \tag{1}$$

where n is the peak number, d is the total film thickness, M_{eff} and A_{eff} are the effective magnetization and the effective exchange constant, respectively.

For surface spin pinning of the Kittel type, the resonance fields H_r must decrease in direct proportion to the mode number n squared. Actually, linear dependences of H_r on n^2 were observed for both the NiFe/Cu/NiFe three-layered structure (inset in Fig. 1) and the Co/Pd multilayer films (Fig. 3), which indicate that common spin-wave resonance spectra are accomplished in these artificially created composite materials.

DISCUSSION OF EXPERIMENTAL RESULTS

The occurrence of a common microwave spectrum in multilayer films is due to the exchange interaction of ferromagnetic layers through intermediate nonmagnetic layers. This statement is clearly demonstrated by the form of the spectrum of the NiFe/Cu/NiFe three-layered structure with $d_{\text{Cu}} > 30$ Å, in which two microwave spectra from individual layers are observed and each microwave peak exhibits a doublet splitting (bonding and antibonding of two oscillator modes due to magnetostatic interaction [8]).

The spectrum of spin-wave resonance at the multilayer (three-layered) structure is evidently due to the passage of exchange spin waves through the Pd (Cu) layers. This fact points to the occurrence of a certain magnetic moment and partial exchange in the intermediate layers of diamagnetic Cu and paramagnetic Pd, that is, to a polarization of atoms of elements in these layers at their limited thickness ($d_{\text{Cu, Pd}} \leq 30$ Å). For the Co/Pd multilayer system, it was possible to calculate a value characterizing this partial exchange (exchange stiffness) of spin-wave propagation (at the wave vector $k \neq 0$) through the Pd layer.

The effective exchange coupling constant A_{eff} of the entire film can be determined by the linear dependence of H_r on n^2 in accordance with the equation

$$A_{\text{eff}} = \frac{\langle M\rangle}{2}\frac{H_i - H_j}{n_j^2 - n_i^2}\left(\frac{d}{\pi}\right)^2, \tag{2}$$

where d is the total film thickness, i and j are microwave peak numbers, and $\langle M\rangle = (M_1d_1 + M_2d_2)/(d_1 + d_2)$. (Note that a single peak of homogeneous ferromagnetic resonance was observed in the spectra of Co/Pd multilayer films at the parallel orientation of films in the external magnetic field [11].)

The effective magnetizations M_{eff} (which were assumed equal to the average magnetization $\langle M\rangle$ of the entire sample) were calculated by the resonance fields measured in the perpendicular and parallel configurations

$$4\pi M_{\text{eff}} = \frac{2H_\perp + H_\parallel}{2} - \sqrt{\left(\frac{2H_\perp + H_\parallel}{2}\right)^2 - (H_\perp^2 - H_\parallel^2)}. \tag{3}$$

Substituting the known values of M_{eff}, H_r, d, and n into Eq. (2) gives effective exchange constants for Co/Pd multilayers for 15 studied films (black circles in Fig. 4).

Applying the theory of wave propagation in media with a periodic layered structure developed by Rytov [13, 14] to the case of spin-wave propagation in metallic multilayer films [15] leads to the following result. The reciprocal value of the effective exchange coupling constant is found as the average value of the reciprocal values of partial exchange constants in individual layers of the multilayer structure

$$A_{\text{eff}}^{-1} = \langle A^{-1} \rangle. \tag{4}$$

Hence, the relation of A_{eff} with the partial exchange constants can be expressed as follows:

$$\frac{d}{A_{\text{eff}}} = \frac{d_1}{A_1} + \frac{d_2}{A_2} + \ldots, \tag{5}$$

where d_1, d_2, etc. are the thicknesses of individual layers of various compositions in multilayer films; A_1, A_2, etc. are the corresponding exchange constants; and $d = d_1 + d_2 + \ldots$ is the period of the multilayer film. It is not difficult to show that, if the condition $d_1 = d_2$ is fulfilled, the equation for A_{eff} [Eq. (4)] is completely equivalent to the equation for A_{eff} obtained for the spectrum of spin waves in the one-dimensional model of an inhomogeneous ferromagnet [16]

$$A_{\text{eff}} = \langle A \rangle [1 - (\Delta A / \langle A \rangle)^2], \tag{6}$$

where $\langle A \rangle = (A_1 + A_2)/2$, and $\Delta A = A_1 - \langle A \rangle = \langle A \rangle - A_2 \equiv (A_1 - A_2)/2$.

According to the Rytov equation [Eq. (4)], the value of A_{eff} for Co/Pd multilayer films must be described by the equation

$$A_{\text{eff}} = \frac{A_{\text{Co}}}{\dfrac{d_{\text{Co}}}{d_{\text{Co}} + d_{\text{Pd}}} + \dfrac{d_{\text{Pd}}}{d_{\text{Co}} + d_{\text{Pd}}} \dfrac{A_{\text{Co}}}{A_{\text{Pd}}}} \equiv \frac{A_{\text{Pd}}}{\dfrac{d_{\text{Pd}}}{d_{\text{Co}} + d_{\text{Pd}}} + \dfrac{d_{\text{Co}}}{d_{\text{Co}} + d_{\text{Pd}}} \dfrac{A_{\text{Pd}}}{A_{\text{Co}}}} \equiv \frac{(\sqrt{A_{\text{Co}} A_{\text{Pd}}})^2}{\tilde{A}}. \tag{7}$$

The effective exchange in Co/Pd multilayer films as calculated by Eq. (7), in which $A_{\text{Co}} = 1.3 \times 10^{-6}$ erg/cm and $A_{\text{Pd}} = 0.1 \times 10^{-6}$ erg/cm, is presented in Fig. 4 as a function of the $d_{\text{Co}}/(d_{\text{Co}} + d_{\text{Pd}})$ ratio. It is clear that Eq. (7) quite satisfactorily describes the experimental results. The deviations of the experimental points from the calculated curve can be explained by natural variations in the values of A_{Co} or A_{Pd} due to imperfections of individual layers.

Thus, in this paper, it is shown that a spin-wave resonance spectrum is observed in the Co/Pd multilayer films and in the NiFe/Cu/NiFe three-layered structure under the condition that the thickness of the nonmagnetic metal is less than a critical value ($d_c \sim 30$ Å). The passage of traveling exchange spin waves through the nonmagnetic layers can be caused by the polarization of atoms in the intermediate layers: a magnetic moment and a certain exchange interaction are induced in these layers. In this case, our experiments allow the depth of the polarization of the layer of nonmagnetic metal atoms by the layers of ferromagnetic 3*d* metals. It was found equal to ~15 Å.

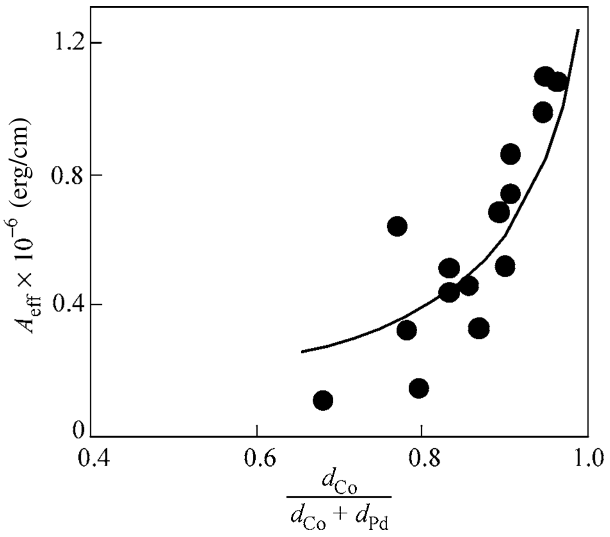

Fig. 4. Effective exchange constant in Co/Pd multilayer films vs. the $d_{\text{Co}}/(d_{\text{Co}} + d_{\text{Pd}})$ ratio as (points) measured from the microwave spectra and (line) calculated according to Eq. (7).

Based on the model of the effective layered medium proposed by S.M. Rytov, the partial exchange stiffness was calculated for a spin wave propagating through a Pd layer ($A_{\text{Pd}} = 0.1 \times 10^{-6}$ erg/cm) in Co/Pd multilayer films.

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