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Spin-Wave Resonance in Multilayer Films (One-Dimensional Magnon Crystals). Identification Rules

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The characteristic modification of the spectrum of the exchange spin waves has been revealed in ferromagnet/ferromagnet multilayer films with a thickness of $N(d_1 + d_2)$ by the spin-wave resonance method. This modification is due to the first bandgap at the wavenumber $k_b = \pi/(d_1 + d_2)$ of a magnon crystal, which is formed by one-dimensional modulation of the magnetization. It has been shown that the transformation of the multilayer film with thermal annealing to the film of a single-phase alloy is accompanied by the disappearance of this modification of the spectrum.

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Studies of multilayer films that are one-dimensional modulated structures, which are manufactured from two materials with different parameters, are stimulated by wide variety of physical effects in them. It is known that the spectrum of waves of any nature in periodic structures is of a band character [1] and contains allowed and forbidden bands of the energy ε. Brillouin zones are formed in the reciprocal space. The edges of these zones are determined by the wavenumber $k_b = mq/2$, where m is the ordinal number of a zone, $q = 2\pi/(d_1 + d_2)$ is the reciprocal lattice vector, and $d_1 + d_2$ is the one-dimensional modulation period. Calculations show that band gaps $\Delta\varepsilon_m$ appear in the $\varepsilon(k)$ plot at these k_b values. The width of a band gap is determined by the difference between the physical parameters of neighboring layers. Photon and magnon crystals, which are actively studied, are among these structures. The aim of this work is to detect coherent magnons in multilayer films near the edge of the Brillouin zone, where the modification of the function $\varepsilon(k)$ occurs, as shown in Fig. 1a.

It is known that the uniform variable field h can excite standing spin waves in thin ferromagnetic films. This phenomenon is called the spin-wave resonance [2, 3]. When the external magnetic field $\mathbf{H}$ is perpendicular to the film plane ($\mathbf{H} \perp \mathbf{h}$), the resonance condition has the form

$$H_n = \frac{\omega}{\gamma} + 4\pi M_{\text{eff}} - \frac{2A}{M_s}k^2. \quad (1)$$

Here, ω is the fixed microwave frequency, $A = 2JS^2/a$ is the exchange constant, and $k = n\pi/L$ is the wavenumber of the spin wave, where n is the order of the mode and L is the film thickness. The dependence of H_n on n^2 makes it possible to calculate the magnetization (M_s and M_{eff}) and exchange constant A. This dependence can be plotted if there is the experimental curve of spin-wave resonance and n is identified by some rules. These rules are reported in [4, 5] (and most completely in [6]). These rules are briefly as follows. If spins are completely fixed on the film surface, only

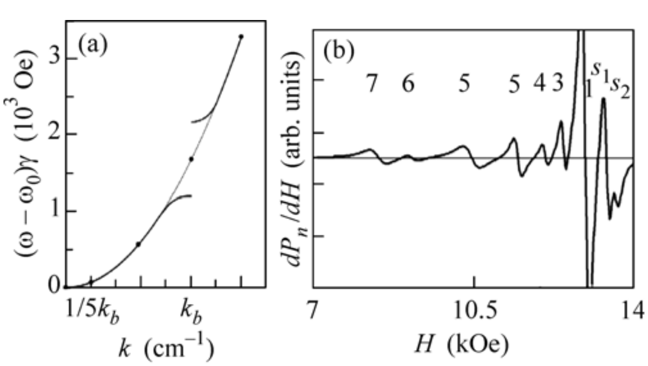

Fig. 1. (a) Solid line is the schematic dispersion law of exchange spin waves in the multilayer film with the thickness $L = 5(d_1 + d_2)$, $k_b = 0.872 \times 10^6$ cm^{-1}. The points connected by the dashed line describe the dispersion law in a uniform ferromagnetic film with thickness $L = 1800$ Å with exchange stiffness $\eta = 2.2 \times 10^{-9}$ Oe cm^2. (b) Spectrum of spin-wave resonance of the multilayer film $[Ni_{65}Fe_{35}(180\,Å)/Ni_{60}Fe_{40}(180\,Å)]_5$. Resonance fields H_n are determined by the zeros of the function dP_n/dH (or the maxima of the function $P_n(H)$).

odd modes ($n = 1, 3, 5, ...$) appear on the curve. If pinning is incomplete, weak, even modes can appear $I_{2n} \ll I_{2n-1}$, $I_{2n} < I_{2n+1}$, $n = 1, 2, 3, ...$, where I_n is the signal intensity, which is proportional to the derivative of the absorbed power P with respect to the magnetic field (dP_n/dH). Moreover, depending on the sign of the pinning (pinning is described by the surface anisotropy K_s), surface spin waves are possible in the spectrum (at $K_s < 0$). The experimental spin-wave resonance technique enables the detection of up to ten standing spin waves in the wavenumber range $k = 10^5$–10^6 cm^{-1}. Therefore, the wavenumber of the edge of the Brillouin zone $k_b = \pi/(d_1 + d_2)$ of the multilayer film with the thickness $L = N(d_1 + d_2)$ should be fitted to the middle of the measured wave range.

The previous experimental studies (see, e.g., [7–11]) of the spin-wave resonance in multilayer films do not satisfy this condition. In those works, the measured wave range was much lower than the wavenumber of the edge of the band $k_b = \pi/(d_1 + d_2)$; the exception to this is [12], where the spin-wave resonance of the Co/Pd multilayer film was examined. In particular, the spin-wave resonance spectrum in [7] completes the $n = 10$ mode at $N = 50$, the wavenumber in [8, 9] is determined for $n = 6$ at $N = 10$, and the spin-wave resonance spectra in [10, 11] are limited by the $n = 7$ mode at $N = 10$ and 12, respectively. The experimental proof of the applicability of Eq. (1) for describing standing spin waves in multilayer films is a significant result of those studies.

As initial materials, we used NiFe/NiFe multilayer films, which are obtained by the chemical deposition. The $Ni_{1-x}Fe_x/Ni_{1-y}Fe_y$ modulated structure was manufactured by varying the concentration of transition metals. The number of pair layers N was 5 ($L = 5(d_1 + d_2)$). The magnetic parameters of the used alloys were as follows. In the $Ni_{60}Fe_{40}$ alloy, the local anisotropy field was $H_a = 3.3$ kOe, the magnetization was $M_0 = 1000$ G, the exchange coupling constant was $A = 1.3 \times 10^{-6}$ erg/cm. In the $Ni_{65}Fe_{35}$ alloy, $H_a = 3.3$ kOe, $M_0 = 800$ G, and $A = 0.83 \times 10^{-6}$ erg/cm. In the $Ni_{80}Fe_{20}$ alloy, $H_a = 2$ kOe, $M_0 = 600$ G, and $A = 0.4 \times 10^{-6}$ erg/cm. In the $Ni_{90}Fe_{10}$ alloy, $H_a = 1$ kOe, $M_0 = 500$ G, and $A = 0.25 \times 10^{-6}$ erg/cm. According to theoretical work [13], the gap in the spectrum of exchange spin waves for the produced structures should be about 1 kOe.

The thicknesses of individual layers d_i were the same, but were different (150, 180, 200, and 250 Å) for different samples. The spectra of ferromagnetic resonance and spin-wave resonance were measured on an EPA-2M standard spectrometer with a frequency of 9.2 GHz with two orientations of the samples with respect to the field H at room temperature. The spectra of the samples that were annealed in a vacuum of 10^{-5} Torr at 100, 200, and 300°C for 1 h were also analyzed.

Figure 1b shows the curve measured on the $[Ni_{65}Fe_{35}(180\ Å)/Ni_{60}Fe_{40}(180\ Å)]_5$ multilayer film. The curve includes ten peaks, which make it possible to completely analyze the spin-wave resonance spectrum. Two peaks in the spectrum of this film correspond to resonance fields higher than the field of the most intense maximum. This means that the wavenumbers k of the standing spin waves are determined from the following equations, which were obtained from exchange boundary conditions at arbitrary parameters of the pinning of the magnetization on the lower and upper surfaces of the film d_1^s and d_2^s:

$$\tan(kL) = \frac{(d_1^s + d_2^s)k}{k^2 - d_1^s d_2^s}, \text{ if } k \text{ is real}, \quad (2)$$

$$\tanh(k_s L) = \frac{-(d_1^s + d_2^s)k_s}{k_s^2 + d_1^s d_2^s}, \text{ if } k \text{ is imaginary} (k = ik_s). \quad (3)$$

Here, $d_i^s = K_{is}/A$ is the pinning parameter. The observation of two surface modes ($n = 0$), which are marked as S_1 and S_2 in Fig. 1b, indicates that exchange boundary conditions with the easy-plane surface anisotropies (K_{1s}, $K_{2s} < 0$) are implemented on the outer and near-substrate surfaces of this multilayer film. The direct measurement of these quantities gives $|K_{1s}| = 2.9$ erg/cm^2 and $|K_{2s}| = 4$ erg/cm^2. Equation (2) for bulk modes in the case of strong pinning ($A/K_sL \longrightarrow 0$) has a Kittel solution, $kL = n\pi$, with the excitation of only odd n values. For the case $|A/K_sL| \ll 1$, we obtain the solution

$$kL \approx n\pi(1 - A/K_sL) = n\beta, \quad (4)$$

where $n = 1, 2, 3, 4, 5, ...$; i.e., both odd (symmetric with respect to the center of the film) and even (antisymmetric with respect to the center of the film) modes are excited in the spectrum. Due to antisymmetry, the intensity of an even mode is smaller than the intensities of the neighboring odd modes. Indeed, the intensity of the fourth mode is smaller than the intensities of the third and fifth modes (see Fig. 1b). For the discussed multilayer film, $\beta = 3.115$. For this reason, to determine the wavenumbers, we can use the Kittel solution because the shift of resonance fields (due to the difference $\pi - \beta$) is an order of magnitude smaller than the width of spin wave modes. The fifth and subsequent modes are of particular interest. The fifth mode is characterized by the wavenumber $k_5 = 5\pi/L = 5\pi/5(d_1 + d_2) = \pi/(d_1 + d_2) = k_b$; i.e., this peak is detected at the low-energy edge of the band gap of the spin wave spectrum (see Fig. 1a). It can be seen (Fig. 1b) that subsequent modes cannot be described with $n = 6$, 7, and 8 because the intensities of these modes are inconsistent with the intensity rule. Therefore, the n values of the low-field peaks of spin-wave resonance of this film should be identified as $n = 5$, 6, and 7. Only this case ensures the intensity rule as $I_5 > I_6$ and $I_6 < I_7$. As a result, the exchange doublet at $n = 5$ is introduced that consists of absorption peaks of the edge of the band gap of the exchange spin wave spectrum, which is described by the modes $n = 1, 2, 3, 4, 5, 5, 6$, and 7 (Fig. 1a), where $k_5 = k_b$. Therefore, modes $n = 1, 2, 3, 4$, and 5 belong to the first Brillouin zone of the magnon crystal and $n = 5, 6$, and 7 belong to the second Brillouin zone. The width of the band gap is measured in the field coordinates as the difference between static fields characterizing the fifth modes. The width of the gap for the spectrum of exchange standing spin waves, which is shown in Fig. 1b, is 1.04 kOe. Recalculating this value to the frequency coordinates, we estimate the width of the band gap in the spectrum of exchange spin waves as $\Delta\omega \approx 3$ GHz. It is interesting that for magnetostatic waves that propagate in the film plane for the one-dimensional magnon crystal, which is formed by lithography from Co and NiFe strips (250 nm in width), this estimate corresponds in order of magnitude to the width of the band gap measured in [14] (about 2 GHz). The asymmetry of the amplitudes and widths of the absorption peaks at the edges of the band gap is remarkable. The effect of the asymmetry of the amplitudes and widths of the high-frequency susceptibility at the edges of the band gap of the spectrum of superlattices was revealed in theoretical work [15] in superlattices with two-dimensional inhomogeneities.

The reliability of the performed identification of n, i.e., the experimental detection of the band gap in the spin wave spectrum is proved by the thermal treatment of this multilayer film. The enthalpy of the mixing of Ni and Fe is negative. For this reason, the multilayer film is a thermodynamic nonequilibrium system. Consequently, thermal annealing will be accompanied by the formation of the film of compositionally uniform permalloy. Figure 2 shows thermal-annealing-induced modifications of the spin-wave resonance spectrum, as well as the effective exchange stiffness $\tilde{\eta}_i$, which is calculated from the spin-wave resonance spectrum from Eq. (1) as $\tilde{\eta}_i = (H_1 - H_i)/(n_i^2 - 1)$. As can be seen, after the first annealing stage, an additional, eight, low-field peak appears, the gap width decreases, and the asymmetry of the low- and high-energy peaks at the edge of the band gap increases. The intensity of the eighth mode indicates the validity of the chosen identification $n = 5, 6, 7$, and 8 of low-field peaks. After the second annealing stage, the spectrum of spin-wave resonance is detected in the single-phase film with the modes $n = 0, 0, 1, 2, 3, 4$, and 5 with the linear dependence of H_n on n^2 for the bulk modes of the spin-wave resonance of this film.

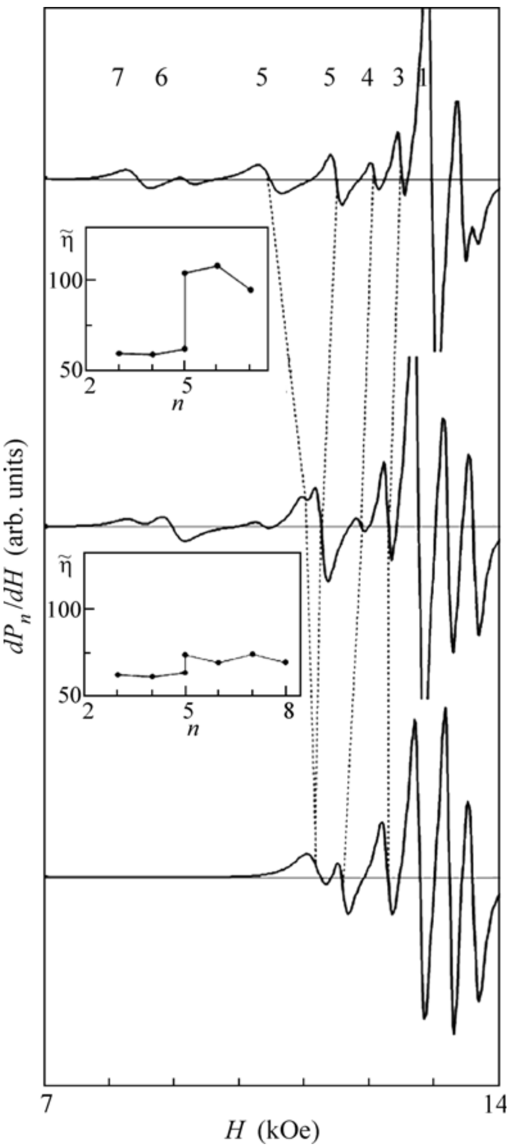

Fig. 2. Transformation of the spin-wave resonance spectrum of the $[Ni_{65}Fe_{35}(180\ Å)/Ni_{60}Fe_{40}(180\ Å)]_5$ multilayer film due to thermal treatment at $T = 200$ and 300°C for 1 h. The insets show the effective exchange stiffness $\tilde{\eta}_i$ (in field coordinates) versus n.

It is known [4, 6] that antisymmetric boundary conditions can be implemented in ferromagnetic films such that easy plane anisotropy ($K_{1s} < 0$) occurs on one surface of the film, whereas easy axis anisotropy ($K_{2s} > 0$) appears on the other surface of the film. If the absolute values of these anisotropies are the same ($K_{1s} + K_{2s} = 0$), Eq. (2) has the Kittel solution; i.e, the homogeneous variable field can only excite spin waves with odd n values and with $n = 0$ in these films.

Figure 3 shows the spin-wave resonance spectrum of the $[Ni_{90}Fe_{10}(150\ Å)/Ni_{80}Fe_{20}(150\ Å)]_5$ multilayer film for which these boundary conditions were

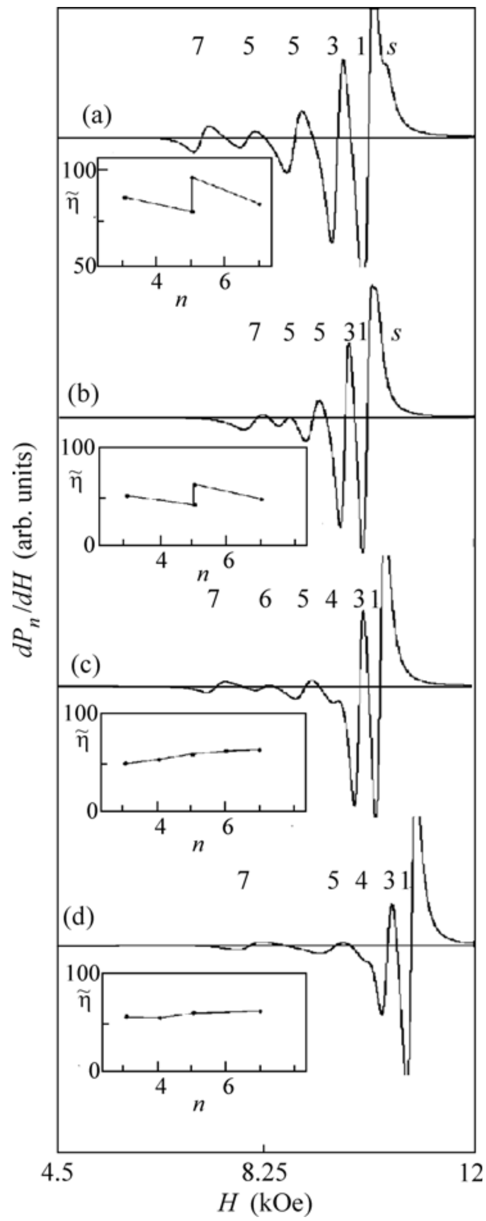

Fig. 3. Spin-wave resonance spectrum of the $[Ni_{90}Fe_{10}(150\ Å)/Ni_{80}Fe_{20}(150\ Å)]_5$ multilayer film (a) in the initial state and after annealing for 1 h at T = (b) 100, (c) 200, and (d) 300°C. The insets show the effective stiffness $\tilde{\eta}_i$ versus the ordinary number of spin-wave mode n.

formed. It can be seen that one surface mode and odd bulk modes are implemented in the spin-wave resonance spectrum of the initial multilayer film. Figure 4 shows the experimental dependence of resonance fields on the square of the mode number. The gap in the field coordinates is 800 Oe. Figures 3 and 4 also present the modification of the spin-wave resonance spectrum during thermal annealing that transforms this modulated multilayer film to the single-phase permalloy layer. The modification of the spectrum of this multilayer film begins even during annealing at 100°C.

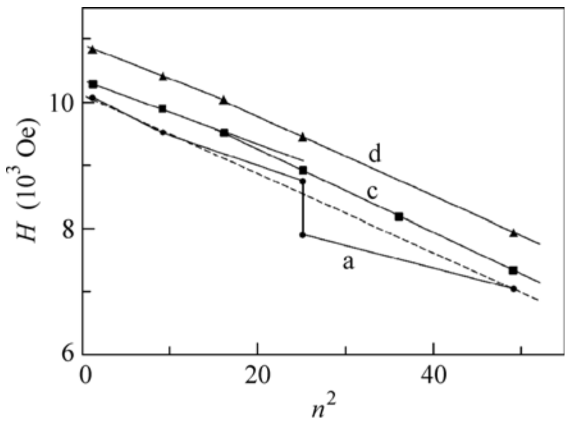

Fig. 4. Plot of $H_n(n^2)$ for the $[Ni_{90}Fe_{10}(150\ Å)/Ni_{80}Fe_{20}(150\ Å)]_5$ multilayer film (a) in the initial state and after annealing T = (c) 200 and (d) 300°C.

A significant decrease in the gap (by a factor of 2 as compared to the initial gap), an increase in the asymmetry of the edge absorption peaks, and the contraction of the entire field range of spin-wave resonance are observed (Fig. 3b). Annealing at 200°C is accompanied by the qualitative rearrangement of the spin-wave resonance spectrum so that the field range is recovered and even modes appear in the spectrum (Fig. 3c). The $H_n(n^2)$ dependence (Fig. 4c) can be represented by two straight lines; therefore, exchange for spin waves with n = 1–4 is constant and the exchange stiffness for waves with n = 5–7 increases. The latter property indicates that the one-dimensional periodic modulation of the magnetization is changed to its isotropic fluctuations, which lead to the corresponding modification of $\tilde{\eta}_i$ and the spectrum of spin waves (see, e.g., [16, 17]). Annealing at 300°C significantly reduces these fluctuations of the magnetization so that resonance fields H_n lie on the linear dependence on n^2 (Fig. 4d).

To conclude, the modification of the spectrum of the spin waves, which is due to the formation of the first and second Brillouin zones of the magnon crystal, has been revealed in one-dimensional magnon crystals, which were manufactured in the form of ferromagnet/ferromagnet multilayer films, by the spin-wave resonance method for spin waves that propagate along the axis of the modulation of spin parameters. The band gap in the spectrum of exchange spin waves has been measured.

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