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# Spin–Wave Resonance in $[Co_xNi_{1-x}]_N$ and $[Co_xP_{1-x}]_N$ Gradient Films

**R. S. Iskhakov[a], L. A. Chekanova[a], and I. G. Vazhenina[b]**

[a] *Kirensky Institute of Physics, Siberian Branch, Russian Academy of Sciences, Akademgorodok, Krasnoyarsk, 660036 Russia*

[b] *Krasnoyarsk Institute of Rail Transport, Krasnoyarsk, 660028 Russia*

*e-mail: rauf@iph.krasn.ru*

**Abstract**—Gradient films of ferromagnetic 3*d* metals with prescribed magnetic potential profile along the film thickness are obtained. It is found that the spin–wave resonance spectrum in these films is characterized by anomalous dependences of resonance fields of spin–wave modes $H_r$ on the mode number: $H_r(n) \sim n$, $H_r(n) \sim n^{2/3}$.

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## INTRODUCTION

Spin–wave resonance (SWR) enables us to study the energy spectra of exchange spin waves in thin ferromagnetic films directly through experiments [1, 2]. The resonance fields of spin modes that correspond to standing exchange spin waves satisfy the familiar Kittel relation $H_r(n) \sim n^2$, where $n$ is the mode number. Due to the experimental manifestation of this dependence, we can measure such fundamental parameters of a magnetic film material as its saturation magnetization and exchange coupling constant [3]. It known that that when adjusted slightly, the Kittel relation describes standing exchange spin waves in ferromagnetic films of both amorphous [4–6] and nanocrystalline [7–9] alloys, along with multilayer films [10–13]. At the same time, two new classes of magnetic materials, diluted magnetic semiconductors and ferromagnetic metal-dielectric nanocomposites, have recently been discovered. Differences between the Kittel spectrum and the experimental spectra of spin waves in films of these materials is observed. More specifically, SWR spectra satisfying the relations $H_r(n) \sim n$ [14, 15] and $H_r(n) \sim n^{2/3}$ [16, 17] have been recorded for these films. This the aim of work was to produce ferromagnetic films based on 3*d* metals open to SWR investigation and having SWR spectra $H_r(n) \sim n$ and $H_r(n) \sim n^{2/3}$. Another aim was to find what generates these spectra.

## EXPERIMENTAL

The spectra of ferromagnetic and spin–wave resonances in films were measured using a standard EPA-2M spectrometer with a pumping frequency of 9.2 GHz at room temperature. Films of $Co_xNi_{1-x}$ and $Co_xP_{1-x}$ 200–250 nm thick were obtained by means of chemical deposition. SWR spectra of these films were characterized by the standard Kittel relation $H_r(n) \sim n^2$ and increased distances between spin–wave modes proportional to the mode number. In addition, surface oscillation peaks were observed in the region of higher fields, indicating the magnitude and sign of surface anisotropy that ensure dynamic magnetization.

Since the Kittel spectrum was recorded in $Co_xNi_{1-x}$ and $Co_xP_{1-x}$ films, we were able to determine effective magnetization $4\pi M_{eff}$ and exchange coupling constant $A$ for these alloys, and to establish the functional dependence of these parameters on the concentration of components $x$.

Gradient $[Co_xNi_{1-x}]_N$ and $[Co_xP_{1-x}]_N$ films were similarly produced by means of chemical deposition. The number of layers $N$ ranged from 7 to 9, with each layer 20–25 nm thick and differing in composition. In terms of the gradient film thickness, the composition was varied monotonously in order to obtain the corresponding dependence $4\pi M_{eff}(z)$ and $A(z)$. Five to seven spin–wave modes were observed in these gradient films, but the Kittel relation was no longer valid for resonance fields $H_r$.

## RESULTS AND DISCUSSION

The SWR spectrum of a gradient $[Co_xNi_{1-x}]_N$ film with thickness $L = 250$ nm is shown in Fig. 1. The SWR spectrum has five peaks with irregular changes in intensity, allowing us to identify even and odd modes (with low and high intensities, respectively). The dependence of resonance fields $H_r$ on $n$ is presented here as well. It can be seen that it satisfies the linear dependence $H_r(n) \sim n$, and the distances between spin–wave modes do not depend on the mode num-

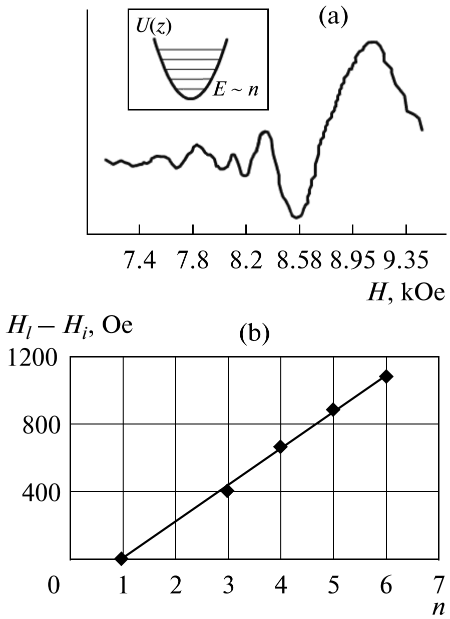


**Fig. 1.** (a) Spin–wave resonance spectrum; (b) dependence of resonance fields $H_r$ of spin modes on the mode number for our $[Co_xNi_{1-x}]_N$ film.

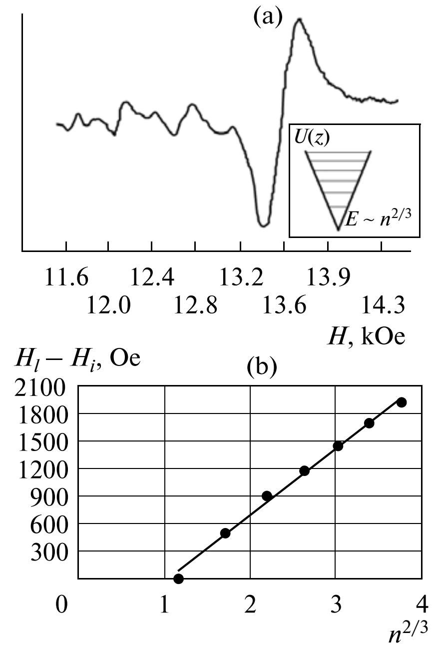


**Fig. 2.** (a) Spin–wave resonance spectrum; (b) dependence of resonance fields $H_r$ of spin modes on the mode number for our $[Co_xP_{1-x}]_N$ film.

ber. It can also be seen that there is no surface mode in the SWR spectrum.

The SWR spectrum of a gradient $[Co_xP_{1-x}]_N$ film with thickness $L = 300$ nm is shown in Fig. 2. The SWR spectrum has seven peaks that can also be divided into odd and even on the basis of their intensities. There is no surface mode (see Fig. 1), and resonance fields $H_r$ satisfy the complex dependence $\left[\frac{3\pi}{2}\left(n+\frac{1}{4}\right)\right]^{2/3}$. It can be seen from the SWR spectrum that the distances between spin–wave modes diminish as the mode number increases.

To interpret our results, we present the motion equation for dynamic magnetization (where $H$ is an external magnetic field):

$$\frac{d^2m}{dz^2} + \left[\frac{\frac{\omega}{\gamma} - H + 4\pi M_{\text{eff}} - \frac{2A}{M_S^2}\frac{d^2M}{dz^2}}{\frac{2A}{M_S}}\right]m = 0, \qquad (1)$$

This equation was derived from the Landau–Lifshitz equation following a standard procedure. The mathematical similarity of the motion equation for the magnetization of films to the stationary Schrödinger equation for particles in single-well potential $U(z)$ must be emphasized. Resonance fields $H_r(n)$ (equal to eigenvalues $E_n$) and the corresponding spin–wave profile $m_n(z)$ (equal to the eigenvector or eigenfunction) are actually similar to the characteristics determined by the solution to the Schrödinger equation. Since the solutions of the Schrödinger equation for various functional dependences $U(z)$ are well-known [18], corresponding assessments of functional dependences of the $U(z)$ type of potential can be based on the type of the functional dependence $H_r(n)$, determined experimentally on the basis of the SWR spectrum. For example, the rectangular well potential leads to the Kittel spectrum. The eigenvalues $E_n$ and $H_r(n) \sim n^2$ and eigenfunctions $\Psi(z)$ and $m(z)$ are trigonometric. The spectrum $E_n \sim n$ is peculiar for a harmonic oscillator, and the magnetic potential for gradient films $[Co_xNi_{1-x}]_N$ may therefore be represented by a parabola.

The $E_n \sim n^{2/3}$ spectrum is peculiar as a result of the triangle-shaped potential $U(z)$, and the magnetic potential in Eq. (1) for gradient films of $[Co_xP_{1-x}]_N$ may therefore be represented by a linear function along the film thickness: $f(z) \sim (z_1 - z)$.

## CONCLUSIONS

It was found that SWR spectra with anomalous dependences $H_r(n) \sim n$ and $H_r(n) \sim n^{2/3}$, which differ considerably from the standard Kittel spectra ($H_r \sim n^2$), can be observed in ferromagnetic metal films based on $3d$ metals by manipulating their magnetic parameters. The obtained results open up new approaches to optimizing the SHF properties of ferromagnetic films.

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