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Spin Wave Resonance in Ni and Its Alloy Films

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The excitation of the spin wave resonance was investigated for various Ni films. The observation was possible only in the case of film prepared on the unheated glass substrate. It was sensitive to the inner crystalline structure of film. The exchange coupling constant A in Ni film was estimated to be $0.75 \times 10^{-6} \text{ erg/cm}$ and the exchange integral J to be 9.4×10^{-14} erg. Similarly Cu-Ni and Pd-Ni alloy films were prepared. These films were confirmed to have the nearly perfect structure by means of the electron diffraction. With increasing content of Cu and Pd, the value of A decreased monotonically to as small as about 1/5 at 22% Cu and 2/3 at 35% Pd, respectively. The exchange integrals of these alloys were, however, nearly constant.

The excitation of the standing spin wave by micro-wave resonance was experimentally confirmed at first in Permalloy films by Seavey and Tannenwald¹⁾. This spin wave resonance could be observed also in some Ni films²⁾ and therefrom the magnitude of the exchange integral was estimated.

Ni films in the present work were prepared by the evaporation in vacuum of 4×10^{-5} mm Hg under various conditions. A cleaved mica or a cleaned cover glass plate was used as a substrate. The substrate temperature was varied from room temperature to 320°C. The effect of the heat treatment was also studied. Some of the films were prepared by the electro-deposition on copper plates.

The film thickness was measured with the multiple beam interferometer. Most of the films in the present work were within the range from 1,000 to 3,000 Å in thickness.

The resonance was observed at 9,300 Mc/sec with the field modulation method. The static magnetic field was applied parallel or perpendicular to the film plane. All the experiments were carried out at room temperature.

The resonance equations are written as follows²:

$$\begin{aligned} (\omega/\gamma)^2 &= \left(H_{\parallel} + 4\pi M + \frac{3\lambda\sigma}{M} + \frac{3\lambda\sigma_u}{M}\cos^2\theta \right) \\ &\times \left(H_{\parallel} + \frac{3\lambda\sigma_u}{M}\cos 2\theta \right), \end{aligned} \tag{1}$$

$$\begin{aligned} (\boldsymbol{\omega}/\boldsymbol{\gamma})^2 &= \left(H_{\perp} - 4\pi M - \frac{3\lambda\sigma}{M} - \frac{3\lambda\sigma_u}{M} + \frac{2A}{M}k^2 \right) \\ &\times \left(H_{\perp} - 4\pi M - \frac{3\lambda\sigma}{M} + \frac{2A}{M}k^2 \right), \end{aligned} \tag{2}$$

where ω is the angular frequency, γ the magnetomechanical ratio (=2.80 πg), M the saturation magnetization, λ the saturation magnetostriction constant, σ the isotropic stress in the film plane, σ_u the uniaxial stress at an angle θ out of the direction of M, A the exchange coupling constant, k the wave number (= $p\pi/L$, L being the film thickness).

The first equation holds in the case of the parallel field H_{\parallel} , and the second one in the case of the perpendicular field H_{\perp} . The spin wave resonance in the case of the parallel field could not be observed for all the films prepared. So, only the case of the perpendicular field is described, hereafter.

The distinct observation of the spin wave resonance was possible only in the cases of the films prepared on the unheated glass plates. It was almost impossible in all the other cases. The films prepared on the heated glass plates did not show any spin wave resonance. All the films prepared on mica, heated as well as unheated, were just so. And the films electro-deposited on copper plates were also in the same case.

The annealing in vacuum acted always so as to make the spin wave resonance in any film to vanish. The heat treatment in air intensified the NiO lines in the electron diffraction patterns, but it made the subsidiary peaks of the spin wave resonance indistinct.

The crystalline structure of those films were investigated with the electron diffraction. The higher the temperature of the substrate was, the sharper the diffraction lines became. With the rise of the substrate temperature, the structure of the film was more homogeneous and the retained stress was smaller.

These facts may show that the possibility to excite the spin wave resonance in Ni film depends not only on the surface conditions of the film, but also strongly on the inner structure, which is influenced by the states of the substrate and by the heat treatment of the film.





Fig. 1. The line profile of spin wave resonance in Ni film with L=2,000 Å and $A=0.66\times10^{-6}$ erg/cm.

Now, a typical example of the spin wave resonance curve is shown in Fig. 1. Corresponding to the respective modes of the spin wave, several resonance points could be distinctly identified. Even as well as odd mode numbers usually appeared.

Since the uniaxial stress is generally very small, the resonance equation (2) can be rewritten as follows:

$$\omega/\gamma = H_{\perp} - 4\pi M - X + \frac{2A}{M} \left(\frac{p\pi}{L}\right)^2 \qquad (2')$$

where X is the stress field. The value of A is derived from the interval between the intensities of the resonance field which correspond to different mode numbers.

In the atomic model the expressions of A and M are given by

$$=nS^2 J/a \tag{3}$$

and

$$M = ng S \mu_B / a^3 \tag{4}$$

where *n* is the number of lattice points per unit cell (n=4 for f.c.c., n=2 for b.c.c.), *a* the lattice constant, μ_B the Bohr magneton, *S* the spin quantum number, *J* the exchange integral. The value of *S* must be considered as the effective value at room temperature. Rigorously speaking, the atomic model has the dilemma of 2*S* being non-integral even at 0°K. The value of *J* to be obtained in the present work is also the effective value.

Table I. Values of A and J in Ni films. (At room temperature, f=9,300 Mc/sec, $a=3.52_4$ A, g=2.18, M=490 and $2S=0.53_2$).

L (Å)	p	$\begin{vmatrix} A (\times 10^{-6} \\ erg/cm) \end{vmatrix}$	J (×10 ⁻¹⁴ erg)
2,000	3~6	0.66	8.3
2,500	3~5	0.83	10.4
1,570	2~4	0.74	9.3
1,570	$2 \sim 4$	0.72	9.0
1,570	2~4	0.80	10.0
mean	Leven Strange	0.75	9.4

The results are shown in Table I. Because of the common nature to the evaporated films, certain fluctuations in the values of Aand J were observed. The mean value of Afor the present films was 0.75×10^{-6} erg/cm and the one of J was 9.4×10^{-14} erg.

There is another way to estimate the exchange integral in a bulk specimen. From the temperature dependence of the saturation magnetization at low temperature, we can evaluate J, making use of the following well known expressions:

$$M = M_0(1 - CT^{3/2}), \quad M_0: M \text{ at } 0^{\circ} \text{K}$$
 (5)

and

$$C = \frac{0.1174}{n(2S)} \left(\frac{k}{2SJ}\right)^{3/2}, \quad k: \text{ Boltzmann constant.}$$

According to the measurement by Fallot³⁾, *C* for Ni was $8.6 \times 10^{-6} ({}^{\circ} K^{3/2})$, so that J= 8.3×10^{-14} erg. This is in good agreement with the present value, in spite of the wide differences between the two processes both in the experimental technique and in the temperature range.

Next, the study was extended into the variations of A and J, when a non-ferromagnetic element was added to Ni as a solute. Cu-Ni and Pd-Ni alloys are suitable for the purpose, because each of them forms continuous series of solid solutions and may be an interesting material from the theoretical point of view.

Following the procedure established for pure Ni, those films were prepared by the evaporation of alloy source onto the unheated glass substrate. The rate of evaporation in this case, however, was made considerably high such as between 500 and 1,000 Å/sec in order to prevent the film from imperfect alloying. The content of a solute was surveyed with



Fig. 2. Composition variation of exchange coupling constant A and exchange integral J for Cu-Ni alloy films.



Fig. 3. Composition variation of exchange coupling constant A and exchange integral J for Pd-Ni alloy films.

the calorimetric analysis and from the measurement of Curie temperature⁴⁾. The electron diffraction patterns of those films revealed that every film had a face-centred cubic structure of single phase and line widths were as sharp as those of pure Ni films. The lattice parameters thus determined were nearly consistent with the data of the x-ray diffraction measured on bulk specimens by other researchers. Furthermore, these results were hardly affected by the annealing at 300°C for one hour. The present films must have nearly perfect structures.

The values of A of those alloys decreased monotonically with the increase of a solute content. In the case of Cu-Ni alloy the value at 22% Cu was about 1/5 of pure Ni, as shown in Fig. 2. In the case of Pd-Ni alloy the decrease was not so rapid. The value at 35% Pd was about 2/3 of pure Ni, as shown in Fig. 3.

The values of J of those alloys obtained formally in the same procedure as in the case of pure Ni are shown in Fig. 2 and Fig. 3, respectively.

Kondorskij et al.⁵⁾ studied the saturation magnetization at low temperatures and estimated the values of J in bulk specimens of Cu-Ni alloys, making use of Eqs. (5) and (6). Their data agree satisfactorily with the present ones.

It is very interesting to see that the magnitudes of the exchange integral thus estimated were nearly constant in any alloy films as far as the present study was performed.

References

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DISCUSSION

P.E. TANNENWALD: Can you attribute any theoretical significance to the results that *J* remains constant upon addition of non-magnetic metals and with changes in temperature?

R. KIMURA: No. Theoretical studies on these points have never been made.