

# Study of the dispersion law for spin waves in amorphous films by the spin-wave resonance method

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Spin-wave resonance was investigated experimentally at 9.2 GHz in Co-P films in the amorphous and crystalline states. A characteristic kink, previously predicted theoretically [V. A. Ignatchenko and R. S. Iskhakov, Sov. Phys. JETP 45, 526 (1977) and 47, 725 (1978)], was observed on the dispersion curve for the spin waves in the amorphous state. The mean square fluctuation of the exchange-interaction parameter and the correlation radius of the fluctuations of this parameter are determined. The previously observed discrepancy between the values of the exchange parameter determined by the spin-wave resonance method and by measuring the temperature dependence of the magnetization is explained.

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A theory of spin waves in amorphous and in finely dispersed media was developed earlier.<sup>[1]</sup> If a phenomenological approach is used, such media are described as having spatially fluctuating parameters. Two characteristic limiting cases we considered separately in Ref. 1:

A) Cases when the principal role is played by fluctuations of the exchange parameter  $\alpha$  (isotropic inhomogeneities).

B) Cases when the principal role is played by fluctuations of the magnitude and direction of the magnetic anisotropy (anisotropic inhomogeneities).

Since we have at present no consistent microscopic theory of amorphous magnetism, the principal characteristics of the fluctuating parameter  $\gamma_i$ , its mean square deviation  $\Delta\gamma_i$ , and the correlation radius  $r_0$  were treated in Ref. 1 as phenomenological constants whose values must be determined from experiment. The dispersion equation obtained for A is

$$\omega = \omega_0 + g\alpha M k^2 \left[ 1 - \left( \frac{\Delta\alpha}{\alpha} \right)^2 \frac{k_0^2 + 5k^2}{k_0^2 + 4k^2} \right]. \quad (1)$$

The dispersion curve (1) has as a function of  $k^2$  a characteristic kink in the vicinity of  $k = k_0/2 = 1/2r_0$ ; the kink is proportional to the relative variance  $(\Delta\alpha/\alpha)^2$  of the fluctuating parameter  $\alpha$ .

The dispersion law for case B is much more complicated: it should contain besides  $k_0$  also the characteristic wave number  $k_H = (H/\alpha M)^{1/2}$ , which depends on the magnetic field H and on the saturation magnetization M.

The results of Ref. 1 were obtained with magnetodipole forces neglected. This restriction was subsequently<sup>[2]</sup> lifted and a theory of spin waves in amorphous and finely dispersed media was developed with allowance for the dipole-dipole interaction. It turned out then that the main conclusion obtained for case A (Ref. 1), namely the presence of a "kink" on the dispersion curve, remains in force. It was impossible to obtain for the dispersion relation an analytic expression

valid in the entire range of variation of  $k$ , but the expressions obtained for the asymptotes (in the system of coordinates  $\omega$  and  $k^2$ ) account for the main character of the behavior of the dispersion law:

$$\omega = \omega_0 + g\alpha M k^2 \left[ 1 - \left( \frac{\Delta\alpha}{\alpha} \right)^2 J(k) \right],$$

$$J(k) = \begin{cases} 1 - k_M^2/2(k_0 + k_M)^2, & k \rightarrow 0, \\ 5/4 - [(k_0/2)^2 - k_M^2]/4k^2, & k \gg k_0/2. \end{cases} \quad (2)$$

Here  $k_M = (4\pi/\alpha)^{1/2}$  is the characteristic wave number of the dipole-dipole interaction; expressions (2) are valid at  $k_M < k_0/2$ . The point  $k_u$  of the kink on the dispersion curve is determined by the intersection of the asymptotes (2):

$$k_u^2 = \left[ \left( \frac{k_0}{2} \right)^2 - k_M^2 \right] / \left[ 1 + \frac{2k_M^2}{(k_0 + k_M)^2} \right]. \quad (3)$$

For case B, allowance for the dipole interaction leads to exceedingly cumbersome integrals, which can be calculated by numerical means if necessary.

An experimental study of the spin-wave dispersion law makes it possible in principle to determine the two most important characteristics of an amorphous magnet—the mean squared fluctuation and the correlation radius.

The dispersion law of the amorphous magnetic Co-P films was investigated by the spin-wave resonance (SWR) method at 9.2 GHz. The structural transformations from the amorphous to the crystalline state in these films were studied previously and reported in Refs. 3 and 4, where the experimental procedure is also described.

We call attention, however, to one important circumstance. To observe the previously predicted<sup>[1,2]</sup> effects of the modification of the dispersion curve it is necessary to observe a sufficiently large number of well-identifiable SWR peaks. This requirement is not satisfied by the customary SWR procedures, in which the resonance is observed as a result of "natural" pinning of the spins on the film surface. In the latter

case, as a rule, it is possible to observe not more than three or four peaks, and the connection between the number of the mode and the value of  $k$  is determined by a transcendental equation that contains a parameter that cannot be readily measured and is difficult to control, namely the surface anisotropy.<sup>[5, 6]</sup>

In this paper, just as in Refs. 3 and 4, we use a special method, justified in Ref. 7, for artificially formulating the boundary conditions for the magnetization vector on the surface of the film. It becomes possible here to observe 9–11 SWR peaks, and the connection between the number  $n$  of the mode and the value of  $k$  is determined by a very simple relation that does not contain the surface-anisotropy parameter:

$$k_n = n\pi/d, \quad n=1, 2, \dots, \quad (4)$$

where  $d$  is the film thickness.

Figure 1 shows the experimental dispersion curves in coordinates  $(H_n, n^2)$  for films of the same composition (9.3 at. % P) but of different thickness. The ordinate is the difference  $H_1 - H_n$ , such that the zero point corresponds to the first resonance mode. Curve 1 characterizes the dispersion relation of a film 2700 Å thick in the crystalline state, while curve 2 is a plot of the dispersion relation of the same film but in the amorphous state. It is seen that the dispersion relation for the amorphous film differ in two respects: a) smaller slope, attesting to a decrease of the exchange parameter; this effect was investigated in detail earlier<sup>[3, 4]</sup>; b) the characteristic kink of the dispersion curve at a certain value of  $n$  (at  $n=5$  in this case); this effect was observed in experiment and is reported in this paper for the first time.

Figure 1 shows also the dispersion relations for amorphous of the same composition but with different thicknesses, 3400 Å (curve 3) and 4000 Å (curve 4). The characteristic kinks of these curves are observed at different values of  $n$ , but it can be easily shown that all correspond to the same wave number  $k_u \approx 5.8 \times 10^5 \text{ cm}^{-1}$ . The change of the slope of the dispersion curves with increasing film thickness is due also to the change of the scale of the abscissa axis. All curves 2, 3, and 4 correspond to the same exchange constant, and become practically congruent when a change is made from the  $n^2$  axis to the  $k^2$  axis. No kinks on the

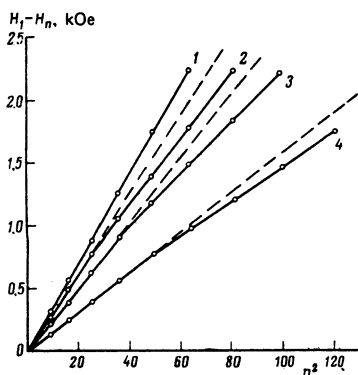


FIG. 1. Difference  $H_1 - H_n$  between the resonant fields vs the square  $n^2$  of the mode number for crystalline and amorphous films of identical composition but different thickness.

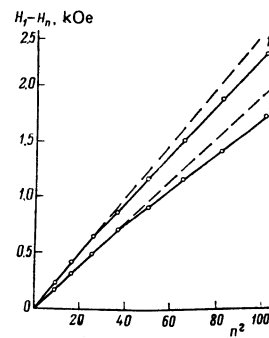


FIG. 2. Difference  $H_1 - H_n$  between the resonant fields vs the square  $n^2$  of the mode number for amorphous films of equal thickness but different composition.

dispersion curves of any of the investigated samples were observed when the films became crystalline.

The picture shown in Fig. 1 corresponds to the modified dispersion relation<sup>[1, 2]</sup> for the case of fluctuation of the exchange constant. This is clearly seen from a comparison of Fig. 1 with Fig. 1b of Ref. 1 and Fig. 1 of Ref. 2. (We note *in passim* that there is a slight inaccuracy in Fig. 1b: a superfluous dash-dot line is drawn below the  $\omega'$  curve.) Fluctuation of the anisotropy would lead to a qualitatively different modification of the dispersion relation for the amorphous state (see Fig. 2 of Ref. 1).

Thus, our films in the amorphous state pertain the case A described by relations (1) and (2). The quantitative comparison of the experimental result should be made with formula (2), inasmuch as in the radio band the allowance for the dipole-dipole interaction is extremely important. In fact, an attempt to reduce the experimental data on the basis of formula (1) leads immediately to a numerical disparity: the coefficient of  $(\Delta\alpha/\alpha)^2$  in this formula can vary, as a function of  $k$ , only from 1 to 5/4, whereas in experiment its variation was by an approximate factor of 2.

In formula (2), the coefficient of  $(\Delta\alpha/\alpha)^2$  varies between limits that agree with experiment, and a comparison of this formula with the experimental data makes it possible to determine all three parameters of the investigated films:  $\alpha$ ,  $\Delta\alpha$ , and  $k_0$ . Reduction of the experimental data by formula (2) leads to the following results: the exchange-interaction parameters of a crystalline film is  $\alpha = 3.2 \times 10^{12} \text{ cm}^2$ ; the mean squared fluctuation of the exchange-interaction parameter in the amorphous state is  $\Delta\alpha = 0.25\alpha$ ; the correlation radius of the fluctuations of the exchange interaction parameter is  $r_0 = 24 \text{ Å}$ . The dispersion curve plotted in accord with formula (2) at these values of the parameters agrees well with experimental curve 2 of Fig. 1.

We have investigated next the dispersion curves of the spin waves of two films having the same thickness but different phosphorus contents. The results are shown in Fig. 2 (curves 1 and 2 are for 9.3 and 11.2 at. % P, respectively). It was already indicated previously<sup>[4]</sup> that an increase of the phosphorus concentration leads to a decrease of the effective exchange constant and to an increase of the degree of disequilibrium of the amorphous films. It is seen from Fig. 2 that in this case the mean fluctuation  $\Delta\alpha$  increases and  $r_0$  de-

creases, as expected from physical considerations.

In conclusion, we shall use formula (2) and the experimental results obtained in the present paper to explain one contradiction that is now under discussion in the literature (see, e.g., Refs. 5 and 6). The point is that the exchange-constant values determined from spin-wave experiments ( $\alpha_s$ ) and from the low-temperature behavior of the magnetization ( $\alpha_m$ ) turned out to be different for amorphous substances. The low-temperature changes of the magnetization are determined by the expression  $\Delta M(T)/M_0 = B_m T^{3/2}$ , where  $B_m \sim \alpha_m^{-3/2}$ . The ratio of the coefficient  $B_m$  to the coefficient  $B_s$ , calculated from the experimental data on SWR ( $B_s \sim \alpha_s^{-3/2}$ ) differ substantially from unity; for example, in Ref. 6 they obtained

$$B_s/B_m = (\alpha_m/\alpha_s)^{3/2} \approx 0.73. \quad (5)$$

To explain this discrepancy, it was proposed<sup>[3]</sup> that the low-temperature behavior of the magnetization in amorphous substances is governed, besides spin waves, also by diffuse modes. The theoretical results<sup>[1,2]</sup> and the experimental results of the present paper provide a different explanation for the discrepancy between  $\alpha_m$  and  $\alpha_s$ . As seen from Fig 1, it is possible to separate to wave-vector regions—the constants preceding  $k^2$  in the function  $H(k)$  are quite different in these regions. The first region is bounded by the kink point—in our case  $k_u = 5.8 \times 10^5 \text{ cm}^{-1}$ . It is precisely in this region, in view of the small number of observed modes, that the constant  $\alpha_s$  was determined by the SWR method. The second region is that of large wave vectors ( $k > k_u$ ), and since the low-temperature behavior of the magnetization is governed by thermal spin waves with wave vector  $k$ , satisfying the inequality  $10^6 \text{ cm}^{-1} \leq k \leq 10^7 \text{ cm}^{-1}$ , it is obvious that the constant

$\alpha_m$  calculated from the temperature dependence of the magnetization can be compared only with the constant  $\alpha_2$  determined by the SWR in this region. From the experimental curve 2 of Fig. 1 we obtain the ratio of the coefficients  $B_1$  and  $B_2$  corresponding to the effective values of the parameter  $\alpha$  in the first and second regions:

$$B_1/B_2 = (\alpha_2/\alpha_1)^{3/2} \approx 0.78. \quad (6)$$

Thus, when the previously obtained<sup>[2]</sup> dispersion relation (2) is used, there are no contradictions whatever between the data of the SWR method and the measured temperature dependence of the magnetization.

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