Ferromagnetic resonance line width in metals and alloys

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(Submitted October 21, 1975)
Pis'ma Zh. Eksp. Teor. Fiz. **23**, No. 5, 280–283 (5 March 1976)

PACS numbers: 76.50.+g

1. The question of the nature of the ferromagnetic resonance (FMR) line in metals, in spite of its ancient history (see, e.g., [1]) still remains unsolved. All that is sufficiently well explained is that part of the broadening which is connected with the skin effect, owing to which the magnetic microwave field excites, instead of a homogeneous precession of the magnetization, a continuous set of spin waves with average wavelengths on the order of the skin-layer thickness. However, the entire aggregate of the experimental data shows that, in addition to this unique inhomogeneous broadening, an important role, and sometimes also a decisive one (for example in alloys), can be played by the usual relaxation broadening due to the damping of the transverse magnetization components excited in FMR.[2–8] Phenomenologically, the relaxation broadening is described with the aid of the damping parameter λ which enters in the known Landau-Lifshitz equation of motion. However, all the attempts at a microscopic calculation of the parameter λ, at finding its frequency, its temperature dependence, and its dependence on the concentration (for alloys), on the magnetization, etc. have led to results that do not agree with experiment.

In this article we propose a relaxation mechanism and present the results of the calculation of the width of the FMR line, which makes it possible to explain many experimental regularities both for alloys (for which two calculations are in fact made), and possibly also for pure metals with defects. The approach is based on the following idea. As before,[1] we consider the cause of the relaxation to be absorption and emission of quanta of quasi-homogeneous precession of the magnetization by the conduction electrons. However, we took into account here the fact that in addition to coherent electron scattering processes (with conservation of the quasimomentum), there occur in alloys and impurity metals also incoherent processes, in which the quasimomentum is not conserved. It is precisely the incoherent processes that make the largest contribution to the FMR line width but the point is that they can be due to such a relatively strong interaction as *sd* (or *sf*) exchange interaction, which turns out to be ineffective (owing to the conservation laws) for coherent processes.

It must be borne in mind, however, that exchange interaction by itself cannot change the total spin of the system, and therefore, the relaxation mechanism indicated above will operate only if there exists an independent (and faster!) relaxation mechanism for the spin of the conduction-electron subsystem. The assumption that the conduction-electron subsystem is in equilibrium is important in principle for the present theory. Finally, with an aim at finding the pure relaxation contribution to the FMR line width, we neglect the skin effect. This means in fact that the depth of the skin effect can exceed the dimensions of the sample, or at any rate is large enough to be able to neglect the spatial dispersion of the magnons. By the same token, we consider the damping of the quasihomogeneous magnetization oscillations.

2. That part of the $sd(f)$ Hamiltonian which is essential for our problem is connected with disorder in the distribution of the atoms of the alloy components over the lattice sites and can be represented in the form

$$V = \frac{1}{N\sigma} \sum_{n\mathbf{k}\mathbf{k}'} e^{-i(\mathbf{k}-\mathbf{k}';\, \mathbf{r}_n)} \Delta(J^{(n)}_{\mathbf{k}\mathbf{k}'} S_n)(a^+_{\mathbf{k}-} a_{\mathbf{k}'-} \sigma^+ + a^+_{\mathbf{k}+} a_{\mathbf{k}'-} \sigma^-). \qquad (1)$$

Here N is the number of unit cells of the principal region of a certain averaged crystal with effective periodic potential, $\mathbf{k}$ is the quasiwave vector of the electron in this crystal, r_n is the radius vector of the $d(f)$ spin S_n, $\vec{\sigma} = \Sigma_n \mathbf{S}_n$ is the summary $d(f)$ spin, which as already been noted, is assumed to be quasihomogeneous, so that $\mathbf{S}_n = S_n \vec{\sigma}/\sigma$ $(\sigma^{\pm} = \sigma_x \pm i\sigma_y)$. The quantity $\Delta(J^{(n)}_{kk'} S_n)$ characterizes precisely the fluctuating part of the $sd(f)$ exchange which is connected with the disorder.

Calculating in the usual manner,[1] by perturbation theory, the average rate of relaxation of the transverse magnetization due to the interaction (1), we obtain the FMR line width $\Delta\omega$ in terms of frequency. In this case $\Delta\omega$ turns out to be proportional to the mean squared quantity $(\Delta(JS))^2$, which, as is well known, determines also the exchange ("magnetic") part of the residual resistivity ρ_M of the alloys, so that $\Delta\omega\ \overline{(\Delta(JS))^2} \sim \rho_M$.

The final result for the line width in an external field, $\Delta H = (\partial\omega/\partial H)^{-1}\Delta\omega$, is expressed by the exceedingly simple formula

$$\Delta H = \frac{e^2 n k_F}{\pi^2} \frac{\rho_M \omega}{M} \qquad (2)$$

Here e is the electron charge, n is their number per unit volume, and $\hbar k_F$ is the Fermi quasimomentum; ω is the FMR frequency and M is the saturation magnetization. We note that inasmuch as the spin disorder is connected in this case with the atomic disorder, we can expect ρ_M as a function of the concentration and of the degree of long-range order to change approximately in the same manner as the total residual resistivity of the alloy. A clearer form of ρ_M can be found in[4].

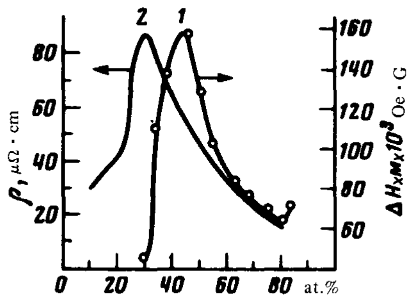
Notice should also be taken of the other important result of the calculation, namely, the absence of an explicit dependence of ΔH (and consequently also of the damping parameter λ) on the anisotropy of the shape of the sample and on the crystalline anisotropy, although they do strongly influence $\Delta\omega$.

On the basis of formula (2) we can explain a number of experimental facts and regularities for ΔH in alloys.

a) Without stretching a point, we obtain the necessary order of magnitude ΔH. Thus, for FeNi alloys we obtain the experimental value $\Delta H \approx 10^2$—10^3 Oe, assuming $\rho_M = 1$—10 $\mu\Omega$ cm (which corresponds to 1—10% of the total resistivity ρ_0).

b) The linear dependence of ΔH on ω, which is observed in many cases,[2,3,5] is explained.

c) The experimental data for FeNi alloys confirm the correlation predicted by formula (2), between the concentration dependences of the product ΔHM and the



residual resistivity. The figure shows, in accordance with the data of[5], a plot of ΔHM against the composition of the FeNi alloy (curve 1). This plot is quite similar to the concentration dependence of the total resistivity of these alloys at 0 °C (curve 2[6]). If we recognize that with decreasing temperature the peak of the resistivity shifts towards larger Ni concentrations, then the similarity of the two curves becomes even more striking.

d) If it is assumed that ΔH remains inversely proportional to M also at finite temperatures, then this explains the temperature dependence of the line width ($\propto 1/M(T)$) observed in molybdenum permalloy,[7] in the alloy $Ni_{0.95}Cu_{0.05}$,[8] and in invar alloys.[9]

4. It is interesting to note that the dependence in the form $\Delta H \sim \omega/M$ is observed sometimes not only for alloys but also for pure metals of the iron group[2] (at sufficiently high temperatures). It is possible that in pure metals, besides impurities, an analogous role is played by defects of various types, and by the sample boundaries, and it is this which leads to the existence of the considered relaxation processes without quasimomentum conservation.

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