MAGNETIZATION OF THIN FERROMAGNETIC FILMS AT LOW TEMPERATURES

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Submitted to JETP editor April 15, 1963

J. Exptl. Theoret. Phys. (U.S.S.R.) **45**, 1156-1158 (October, 1963)

Ferromagnetism in thin films is treated on the basis of spin-wave theory. Because of quantization of the quasimomentum perpendicular to the plane of the film, a gap appears in the energy spectrum of the ferromagnons. Taking the quantization into account leads to an exponential dependence of magnetization on temperature in the low-temperature region. Results of numerical calculations of the dependence of the magnetization on temperature and on film thickness are presented.

A distinguishing characteristic of thin films is the quantization of the perpendicular projection of the quasimomentum, which determines the states of the various quasiparticles in the film. As a result, the states are distributed in the k_xk_y plane in the Brillouin zone (the z axis is taken perpendicular to the film); this leads to a number of effects that occur only in thin films. [1] In the treatment of ferromagnetism in films it is also necessary to take into account the quantization of the perpendicular projection of the quasimomentum k_z.

Exact values of the energy of the spin waves (magnons) can be found only by rigorous quantum-mechanical treatment. However, it is possible to find approximate values of the energy by using the dispersion relation for massive specimens,

$$E = Ak^2, \tag{1}$$

and supposing that k_z takes discrete values. We determine the smallest value of k_z from the uncertainty principle: $k_{min} \approx \pi/L$. Thus the spectrum of the magnons in thin films contains an energy gap.

From what has been said, it follows that the magnetization of the film is determined by the formula

$$M = M_0\Big(1 - \sum_{n=1}^{m} \frac{a^2}{2\pi m} \int_0^\infty dg^2 \Big[\exp\Big\{\frac{Ag^2 + b_n}{kT}\Big\} - 1\Big]^{-1}\Big), \tag{2}$$

where $g = \sqrt{k_x^2 + k_y^2}$, m is the number of atomic layers in the film, a is the lattice parameter, $n = 1, 2, 3, \ldots$,

$$b_n = A\pi^2n^2/L^2 + \text{anisotropy energy},$$

L is the film thickness, and A is expressed in a known form in terms of the Curie temperature for massive specimens. For a simple cubic lattice, $A = k\Theta_C a^2/3.9$, where Θ_C is the Curie temperature. Since in films the anisotropy field is of the order of a few oersteds, it is possible to neglect the anisotropy energy in the expression for b_n up to thickness of order 10^{-4} cm. The smallest value of the energy of a magnon, b_1, is of order 5°K at thicknesses of order 10^{-6} cm.

Formula (2) differs from the corresponding formula for massive specimens in that, in it, the integration is carried out over the two-dimensional k_xk_y space. If the energy gap b_1 in the spectrum of the magnons is equal to zero, the twofold integral diverges logarithmically at zero, and ferromagnetism is impossible. But the presence of the energy gap leads to an exponential decrease of the number of magnons on diminution of temperature. At low temperatures the second circumstance is the more important. Consequently the magnetization of the film should be larger than in a massive specimen. At high temperatures, on the contrary, the magnetization will be smaller; this can lead to a shift of the Curie point into a lower-temperature region.

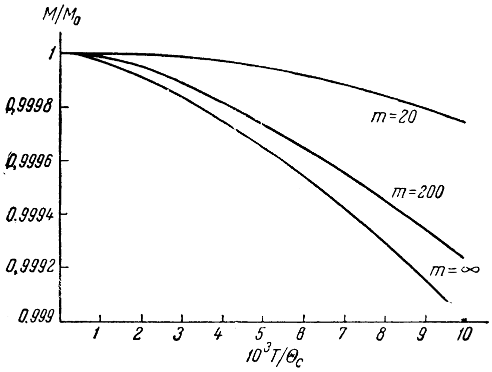

FIG. 1. Dependence of the magnetization of a film on temperature at various thicknesses.

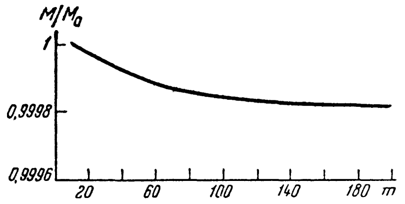

FIG. 2. Dependence of the magnetization on film thickness at temperature 4×10^3 °K/Θ_C.

A similar treatment of the magnetization of ferromagnetic films was carried out by Klein and Smith[2] and in subsequent works that generalized their results. In these works, however, the presence of an energy gap, caused by quantization of k_z, was not taken into account. In [2] the minimum value of k_z was taken equal to zero; this contradicts the uncertainty principle. On the other hand, the minimum values of k_x and k_y were taken not equal to zero, although the quantization of k_x and k_y is unimportant in a film. Consequently our results for low temperatures—and only at these is the spin-wave approximation correct—are directly contrary to the results of Klein and Smith. Furthermore, in [2] the magnetization depends on the area of the film and vanishes when the area of the film becomes infinite; this is quite unnatural.

Integration of (2) gives

$$M = M_0\left\{1 + \frac{3.9}{2\pi}\frac{1}{m}\left(\frac{T}{\Theta_C}\right)\sum_{n=1}^{m}\ln\left(1-\exp\left(-\frac{\pi^2}{3.9}\frac{1}{m^2}\frac{\Theta_C}{T}n^2\right)\right)\right\}. \quad (3)$$

Results of calculations with formula (3) are presented in Fig. 1. Figure 2 shows the dependence of the magnetization of the film on the thickness at a fixed temperature.

We have estimated the minimum value of k_z from the uncertainty principle; therefore we can be sure only of the order of magnitude. Actually the dependence of the magnetization on temperature and thickness may differ from that calculated with respect to the scale along the temperature or thickness axis.

As far as we know, there are at present no works in which the magnetization of thin films was measured at low temperatures. Experimental possibilities,[3] however, at the present time permit the carrying out of the appropriate measurements at low temperatures with the necessary accuracy.

In closing, we express our deep gratitude to M. Ya. Shirobokov for constant interest in the work and for helpful comments; to V. Sokolov and V. Shpiro for discussions; and to Yu. Ketkov and T. Yampol'skiĭ for carrying out the calculations.

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Translated by W. F. Brown, Jr.
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