INFLUENCE OF THE DE HAAS-VAN ALPHEN EFFECT ON THE HELICON WAVE SPECTRUM IN A METAL

D. É. ZHEREBCHEVSKIĬ and É. A. KANER

Khar'kov State University

Submitted March 29, 1969

Zh. Eksp. Teor. Fiz. 57, 1271–1273 (October, 1969)

We consider the effect of quantum oscillations of the magnetic susceptibility on the helicon wave spectrum and the surface impedance of a plate at low temperatures. It is shown that the de Haas-van Alphen effect leads to a significant change in the shape of the resonance curve.

In the determination of the helicon wave spectrum in a nonferromagnetic metal, the magnetic susceptibility is usually neglected. However, if the metal is at sufficiently low temperatures ($T \lesssim 1^\circ K$) in a strong magnetic field H, even a small deviation of the magnetic induction B in the metal from the value of the external magnetic field can play an important role. This is connected with the fact that the differential magnetic susceptibility dM/dB entering into the helicon wave spectrum can be rather large even in the case $|M(B)| \ll H$, where M(B) is the magnetization of the metal.

Vol'skiĭ and Petrashov[1] investigated the influence of the de Haas-van Alphen effect on the spectrum of the helicon wave at comparatively high temperatures ($T \gtrsim 1^\circ K$), when the differential susceptibility is small in comparison with unity. It was established in[1] that the experimental data agree very well with the theoretical formulas. In the present note, the influence of the de Haas-van Alphen effect on the helicon wave spectrum is studied in the region of low temperatures, when a magnetic domain structure can exist in the metal.[2]

We shall consider the propagation of a helicon wave in a metallic plate of thickness d, situated in a constant magnetic field making an angle θ with the normal to the surface of the plate. The wave is propagated perpendicular to the surface of the plate. The Maxwell equations can be written in the form

$$\operatorname{rot}[\mathbf{b} - 4\pi(\mathbf{b}\nabla_{\mathbf{B}})\mathbf{M}] = \frac{4\pi}{c}\hat{\sigma}\mathbf{E}, \quad \operatorname{rot}\mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{b}}{\partial t}, \tag{1}$$

where **b** and **E** are the vectors of the magnetic induction and the electric field of the wave, respectively, and $\hat{\sigma}$ is the conductivity tensor. In the solution of these equations, we shall consider the case

$$\epsilon\ 1 - 4\pi dM/dB > 0,$$

when there is no domain structure. In this case, the magnetic susceptibility is a rapidly oscillating function of B and does not depend on the coordinates. Equation (1) has a solution in the form of a weakly damped helicon wave, the spectrum and damping of which are determined by the formula

$$\omega = \frac{k_m{}^2 c|\cos\theta|}{4\pi ne} B\sqrt{1 - 4\pi\sin^2\theta\frac{dM}{dB}}\left(1 - \frac{i\nu}{\Omega|\cos\theta|}\right), \tag{2}$$

where e is the absolute value of the electronic charge, Ω the cyclotron frequency, n the concentration of conduction electrons, ν the frequency of their collisions with scatterers, and $k_m = \pi m/d$ the wave vector, which takes on a discrete set of values. Depending on the excitation capacity of the helicon wave, m can be either an even or an odd integer. The field of such a wave has the form

$$\mathbf{E}_\perp = \mathbf{E}_0 \exp[i(\mathbf{kr} - \omega t)]; \quad E_\parallel = 0.$$

We consider the dependence of the surface impedance Z on the magnetic field for the excitation of a helicon wave with fixed frequency ω in the plate of thickness d:[3]

$$Z_m = \frac{4\pi\omega}{k'c^2d}\frac{k'' - i(k' - \pi m/d)}{k''^2 + (k' - \pi m/d)^2}. \tag{3}$$

The dependence of the wave vector $k = k' + ik''$ on the magnetic field is determined in the first case by the expression (2). To make clear the dependence of the surface impedance on the magnetic field, it is necessary to find the resonance values of the field, for which $k'(B) = \pi m/d$. These values can be obtained graphically. Here we write down the resonance condition in the form

$$\frac{4ne\omega d^2}{\pi cm^2|\cos\theta|}\frac{1}{B} = \sqrt{1 - 4\pi\sin^2\theta\frac{dM}{dB}} \tag{4}$$

and construct the dependence of the left and right sides of Eq. (4) on 1/B on one graph. The form of these dependences is determined by the conditions of the experiment, i.e., by specifying the parameters ω, T, and θ. At high temperatures ($T \gtrsim 10^\circ K$), when the value of the differential magnetic susceptibility can be neglected, the solution of Eq. (4) is the point of intersection of the straight line which shows the dependence of the left hand side of (4) on 1/B with the line y = 1. For sufficiently low temperatures, Eq. (4) has a series of solutions and some of them can differ appreciably from the solution in the case of high temperatures. The solutions of Eq. (4) are the points of intersection of the straight line in Fig. 1, which corresponds to a definite value of m, with the lines representing the dependence of the right hand side of (4) on 1/B. We note that the problem here is only of points lying above the dash-dot line $y = |\cos\theta|$ in Fig. 1, i.e., of points for which the inequality $4\pi\, dM/dB < 1$ is satisfied.

Now, knowing the resonance values of the magnetic induction, we plot the dependence of the surface impedance on 1/B. For comparatively high temperatures, the curve of the surface impedance has the form shown in Fig. 2. The resonance line has a fine structure. The

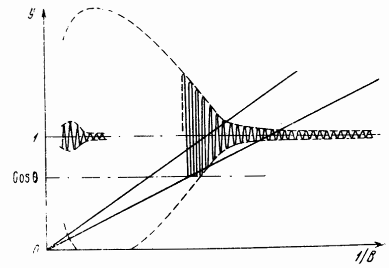

FIG. 1. Graphical solution of Eq. (4). The values of the left and right parts of Eq. (4) are plotted along the Y axis. The straight lines on the graph indicate the dependence of the left hand side of (4) on 1/B for m = 1 in some possible cases. The dashed lines show the path of the dependence of the envelope of the right side of (4) on 1/B for different temperatures ($T_1 > T_2$). In order not to make the graph complicated, the dependence of the right side of (4) on 1/B has been partially omitted for the temperature T_2.

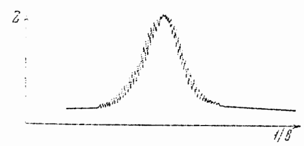

FIG. 2

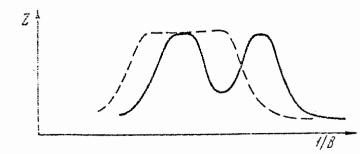

FIG. 3

FIG. 2. Dependence of the impedance on 1/B for comparatively high temperature T_1 ($T_1 \gtrsim 1°K$).

FIG. 3. Two possible forms of the curve of the surface impedance at low temperatures. The fine structure of the lines is not shown.

value of the fine structure is proportional to the slope of the resonance line $dZ(B)/dB$ and to the maximum value of dM/dB over the period of the de Haas-van Alphen oscillations. The value of the fine structure can be determined more accurately by graphical means, using Fig. 1.

The plot of the surface impedance changes markedly at sufficiently low temperatures. The form of the graph depends on the conditions of the experiment. The dependence of the surface impedance on 1/B in some possible cases is shown by the solid and dashed lines in Fig. 3. In the former case, there is an additional resonance peak. In the other possible case, the resonance peak is significantly broadened, changing its shape. The fine structure is rather large, and its value can be obtained by using Fig. 1. The plot of the impedance against B actually represents the dependence on the external field, inasmuch as the difference between B and H is small and can be important only in the oscillating part of the differential susceptibility.

Thus, the study of the helicon wave spectrum at sufficiently low temperatures allows us to establish directly the presence of a magnetic domain structure in metals.

[1] E. P. Vol'skiĭ and V. T. Petrashov, ZhETF Pis. Red. **7**, 427 (1968) [JETP Lett. **7**, 335 (1968)].
[2] J. H. Condon, Phys. Rev. **146**, 526 (1966).
[3] É. A. Kaner and V. G. Skobov, Usp. Fiz. Nauk **89**, 366 (1966) [Sov. Phys.-Uspekhi **9**, 480 (1967)].

Translated by R. T. Beyer
148