Helicon damping in a metal with diamagnetic domains

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A rapid growth of helicon damping was observed in aluminum single crystals as the temperature was lowered below 1 K in a magnetic field exceeding 25 kG. A similar effect was observed also in single-crystal copper.

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The influence of the transition of a metal into a state with diamagnetic domains[1] on the characteristics of helicon waves has not been investigated heretofore. Experimental work of this type is made difficult by the need for producing highly perfect samples with homogeneous crystal structure.

The bulk of the present work was performed on single-crystal aluminum samples in the form of rectangular plates measuring $8\times8\times1.2$ and $4\times4\times1.2$ mm. These samples were prepared by modern metal-physics methods of obtaining single crystals and monitoring their quality: the method of recrystallization after critical deformation[2] and x-ray methods in which sharp-focusing sources are used.[3] The results were samples in which the maximum disorientation of any region on an area of about 1 cm^2 was less than $1'$, and the Dingle temperature for the γ orbits was 0.05—0.1 K.

The measurements reported here were performed in the temperature interval 0.45—4.2 K in a magnetic field up to 60 kG. The experimental setup and the measurement procedure were the same as in[4].

Proceeding to a description of the results, we note first the unusually large amplitude of the sample resonant-frequency oscillations, originating with the extremal sections of the hole Fermi surface of the aluminum, as functions of the magnetic field. At 1.3 K and with the magnetic field directed along the [111] axis, these oscillations can be observed starting with 20 kG, and we have observed no beats whatever on these oscillations. It appears that the beats reported in[5] were caused by some imperfections in the crystal.

The effect described in this paper is illustrated by the series of experimental plots on Fig. 1, obtained with a 48-kG magnetic field directed along [111] accurate to 1°. The upper curve, which is a plot of $f_{\mathrm{res}}(H)$, show the points along the period of one oscillation from the hole Fermi surface, at which points the resonance curve of the sample was recorded as a function of the frequency.

Lowering the temperature produced first, in full accord with formula (33) of[6], an increase of the amplitudes of the oscillations of both the resonant frequency and the height of the resonance maximum (without a significant change in the Q of the resonance). The picture is radically changed at a temperature close to 1.1 K (see Fig. 1). The Q of the resonances decreases at

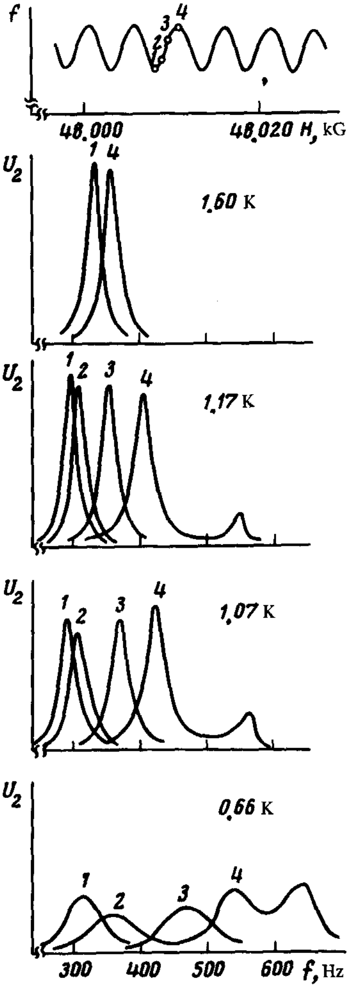

FIG. 1. Resonance curves of first number of resonance of helicons at various temperatures with the magnetic field fixed at points 1, 2, 3, and 4 along the period of one oscillation on the upper curve. The upper curve shows a plot of the sample resonant frequency against the magnetic field at $T=1.3$ K. Aluminum sample, $4\times4\times1.2$ mm, magnetic field parallel to the [111] axis and at an angle 40° to the normal to the surface.

the points near the minimum of the sample resonant-frequency oscillations. With further decrease of temperature, the effect becomes stronger. At the points corresponding to the maximum of the resonant frequency, the satellite peaks are seen to grow and to come closer in frequency to the fundamental resonance.

The experimental points on Fig. 2 are the result of the reduction of a series of curves for one aluminum sample; some of the curves are shown in Fig. 1. The key to the interpretation, in our opinion, lies in the behavior of the resonant frequencies of the sample at the maximum and minimum of the oscillations (Fig. 2b).

In the case under consideration, when the magnetic field is parallel to the symmetry axis and consequently the magnetic moment is parallel to the magnetic field inside the metal, the resonant frequency is proportional to the oscillating factor[7]:

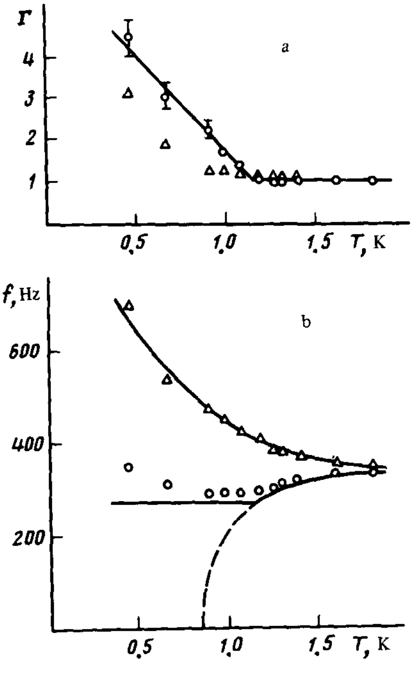

FIG. 2. Temperature dependences of the damping (relative width of the resonance) and of the resonant frequency of the helicon at the maximum (triangles) and at the minimum (circles) of the oscillation for the series of curves on Fig. 1.

$$f_{\text{res}} = f_0 \left(1 - 4\pi \frac{\partial M}{\partial B} \sin^2\theta\right)^{1/2},$$

where θ is the angle between the magnetic field and the normal to the sample surface.

Figure 2(b) shows a comparison of the experimental points with the temperature dependence obtained by substituting in the foregoing formula the values of $\partial M/\partial B$ calculated in accordance with the paper by Lifshitz and Kosevich[8] for $m^* = 1.3m$ (solid and dashed curves, respectively). The segment of the horizontal line corresponds to the value of f_{res} at $4\pi(\partial M/\partial B) = 1$. We see thus that at the same temperature at which the helicon damping begins to grow at the minimum of the oscillations[1)] (Fig. 2a) the resonant frequency at the minimum of the oscillations approaches the value corresponding to establishment of a domain structure in the sample, after which it depends little on the temperature, in agreement with the behavior of $\partial M/\partial B$ of the sample if domains are present in it.[1]

We observe the described phenomenon in aluminum at all magnetic-field directions for which the oscillations due to the hole Fermi surface of the second zone are large enough. Preliminary experiments with a copper field in a magnetic field along the [100] axis have revealed the same effect.

Since there is no theory that describes the electrodynamics of helicons in a metal with diamagnetic domains, we cannot interpret many of our results (for example, the behavior of the satellite resonance). Even the nature of the

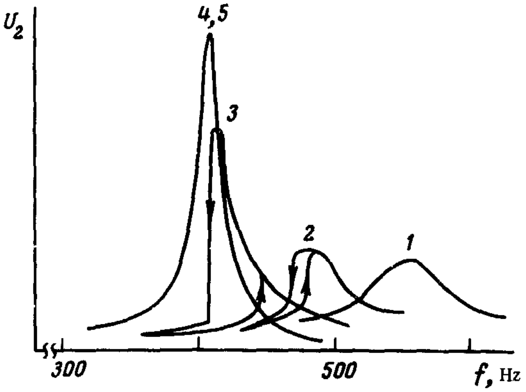

FIG. 3. Resonance curves for an aluminum sample ($8\times8\times1.2$ mm) in a magnetic field of approximately 48 kG, parallel to [111] and fixed near the maximum of the oscillation at $T=0.65$ K. The helicon field amplitude averaged over the sample is 0.15, 1.5, 5, 15, and 50 G for curves 1, 2, 3, 4, and 5, respectively. The period of the oscillations is 5.5 G.

main effect—the increased damping of the helicon—is unknown, although its connection with the establishment of the domain structure in the sample seems quite obvious.

We note also the essential nonlinearity of the effect, i.e., the helicon-field amplitude dependence, which is clearly illustrated by the experimental curves of Fig. 3.

The effect described here has apparently been observed by us earlier.[9] However, the highly developed mosaic structure of the crystal used in[9] has led to a superposition of specific parasitic effects[10] and to an erroneous interpretation.

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1) The growth of the damping at the maximum of the oscillation is apparently connected with the inhomogeneity of the magnetic field along the sample.

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