complete round trip. This feature is seen more clearly in the lower trace of Fig. 1, which exhibits the pulses on an expanded time base.

The dimensions of the quartz rod used in this experiment were 3 cm (length) by 0.3 cm (diameter), with the x axis along the length of the rod. The characteristic time (2τ) between pulses was about 11 microseconds, and the pulse duration, two microseconds. The peak rf power incident upon the transmitter cavity was 25 watts, derived from a 4J50 magnetron.

In Fig. 1, the first dozen or so pulses appear to have nearly the same amplitude due to saturation of the receiver. After correction for this effect, the amplitude of each successive pulse is as shown in Fig. 2, where the third echo pulse is normalized to 100. The pulse decay envelope is seen to be more complicated in detail than the expected simple exponential drop-off. The details of the decay curve appear to be a function of the microwave electric field configuration at the point of coupling in the transmitting cavity and of the particular quartz rod employed. Thus the irregular decay may be caused by partial coupling to other elastic modes of the rod in such a way that energy is alternately exchanged between them. This detail is under further investigation.

When the temperature is varied from 1.8°K to 20°K, it is found that the average attenuation

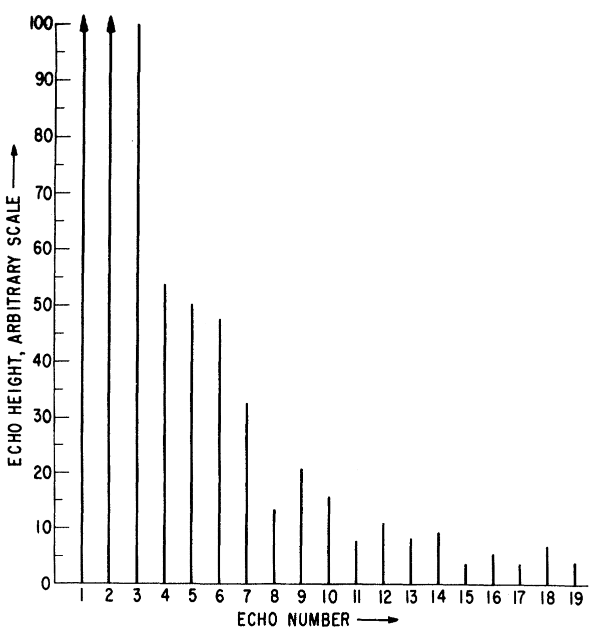

FIG. 2. Graph of relative echo amplitudes after correction for receiver saturation. Third echo pulse is normalized to 100.

increases somewhat more rapidly than linearly with temperature. At 77°K no ultrasonic wave propagation was observable. It is expected that umklapp processes will become effective in attenuating the wave in the temperature range between 20°K and 77°K.

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MAGNETIC OSCILLATIONS OF ULTRASONIC ATTENUATION IN A COPPER CRYSTAL AT LOW TEMPERATURES*

R. W. Morse and J. D. Gavenda†
Department of Physics,
Brown University,
Providence, Rhode Island
(Received February 24, 1959)

In an earlier communication[1] we reported an apparently oscillatory dependence of ultrasonic attenuation in a polycrystalline sample of copper, this occurring at helium temperatures where the electron mean free path (l) was comparable to the ultrasonic wavelength (λ). The results were explained in terms of resonant conditions between the electron orbit diameter and the spatially periodic fields carried by the wave. It was shown that the average Fermi momentum calculated from such a picture was consistent with a value for copper of one free electron per atom. These measurements, however, were deficient in several obvious respects. Only one or two maxima and minima were discernible, and a polycrystal was used because at that time a single crystal of sufficiently long mean free path was not available. Furthermore, a subsequent theoretical analysis by Rodriguez[2] has suggested that such an oscillatory effect would not be expected (at least from a classical Boltzmann equation analysis), and so it was proposed that the observed effect was perhaps a consequence of the polycrystalline nature of the sample.

Here we report some more recent measurements made in a very pure copper single crystal which verify that a pronounced oscillatory effect is indeed found. Moreover, this effect is significantly anisotropic, suggesting that ultrasonic methods should be useful in obtaining information about details of the electronic properties of metals.

Attenuation measurements were made of both longitudinal and shear waves at frequencies between 15 and 75 Mc/sec and in magnetic fields of various orientations at strengths up to 6500 gauss. The temperature was varied between 1.0° and 4.2°K but the results were found to be essentially temperature-independent, indicating that l was determined by impurity scattering. The attenuation was measured by observing a 1-μsec ultrasonic pulse reflected between two highly parallel faces of the sample, these being separated by about 1.25 cm. The faces of the samples were oriented with respect to the crystalline axes to an accuracy better than $\frac{1}{2}$°.

Figure 1 shows the results for a longitudinal wave of 75 Mc/sec propagated along the [001] direction. The magnetic field was applied in a plane normal to the propagation direction and could be rotated about this axis. Since the oscillatory effect should be periodic in H^{-1}, the results are plotted in Fig. 1 on a reciprocal scale. Figure 1(a) shows data for H along either a [100] or a [010] direction. About seven maxima and minima are found which are quite accurately periodic in H^{-1}. Only slightly different results are found for H within about ±15° of these directions. However, with H in the vicinity of the 45° directions, such as [110], the oscillations are changed considerably, a typical result being shown in Fig. 1(b).

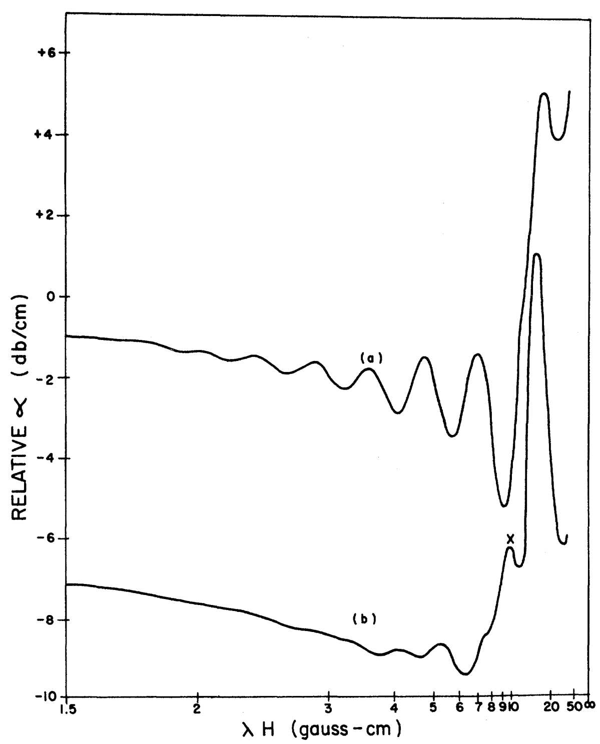

FIG. 1. Attenuation along [001] of 75-Mc/sec longitudinal wave vs λH plotted on reciprocal scale. Curve (a) is for H in the [100] direction, and (b) is for H in the [110] direction. Attenuation is measured relative to that for $H = 0$, with the (b) curve arbitrarily displaced downward by 6 db/cm.

Although no satisfactory theory for such oscillatory behavior now exists, it is of interest to observe that the results are consistent with a model of the Fermi surface proposed by Pippard based on his observations of the anomalous skin effect.[3] In the ultrasonic effect one would expect the greatest contribution to come from those electrons in an extremal cross section normal to the direction of H. Pippard suggests that the Fermi surface in copper touches the zone boundary in the [111] directions, but is nearly spherical elsewhere. Thus for H along the principal axes the relevant electrons would lie on a nearly circular cross section of the Fermi surface. This is the orientation where the well-defined periodic effect is found. On the other hand, when H is along a 45° direction the relevant electrons are on a cross section that is broken up into four segments by the zone boundaries. Experimentally, it is in these directions that one sees a more complicated effect. In particular, another oscillation of a different period seems to enter. A maximum of this other period is designated by × in Fig. 1(b).

One can make an estimate of the Fermi momentum (p_f) from the measurements shown in Fig. 1. If it is assumed that between adjacent maxima the average orbit radius changes by $\lambda/2$, and that $\bar{r} = \bar{p}_\perp c/eH$, where $p_\perp$ is the momentum component perpendicular to H, then one finds $\bar{p}_\perp = 1.16 \times 10^{-19}$ g cm/sec for H along a principal axis. It seems likely that it is some average of $\bar{p}_\perp$ that matters and not the extremal value $p_\perp$. If the assumption of a spherical shell is used, then $\bar{p}_\perp = (\pi/4)p_f$, or $p_f = 1.47 \times 10^{-19}$ g cm/sec. According to Pippard's estimate, p_f in the extremal cross section perpendicular to [100] varies between 1.39×10^{-19} and 1.44×10^{-19} g cm/sec.

Contrary to the results in the polycrystal, the attenuation does not seem to approach zero as H becomes large (at least in all orientations). A similar effect was noted earlier in a tin single crystal.[4] The attenuation at high values of the field (i.e., for $\bar{r} < \lambda/2$) also is found to be highly anisotropic in copper, this dependence being shown in Fig. 2. The angular variation shows a fourfold symmetry which is distorted somewhat, probably because of unavoidable misalignment with respect

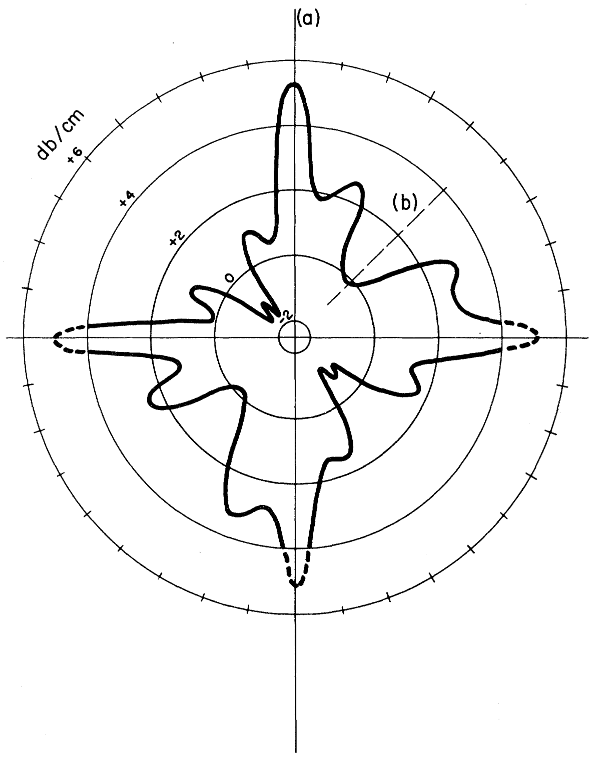

FIG. 2. Attenuation along [001] of 75-Mc/sec longitudinal wave vs the direction of H about the [001] axis, where $H = 6500$ gauss. The direction (a) corresponds to [100] and (b) to [110]; these are the directions in which the curves shown in Fig. 1 were taken. The attenuation scale is relative to that at $H = 0$.

to the magnet. The interpretation one should place on this polar pattern is not clear. Rodriguez's theory predicts in this situation that the high-field attenuation should become proportional to $\omega^2\tau$ (where ω is the angular frequency of the wave and τ is the electron relaxation time). Thus the pattern shown in Fig. 2 may reflect anisotropy of τ as well as of the Fermi surface.

Preliminary measurements also have been made of the attenuation of a plane polarized shear wave with H along the direction of propagation. As pointed out by Kjeldaas, this configuration is interesting because certain groups of electrons, selected by the value of the magnetic field, remain in resonance with the periodic fields.[5] The results at the lower frequencies agree qualitatively with Kjeldaas' predictions except that the experimental attenuation initially increases with H. The attenuation at high frequencies does not diminish with increasing H as rapidly as the theory predicts. However, this may be due to a magnetically induced rotation of the plane of polarization, an effect predicted by Kjeldaas. These results, as well as measurements in other crystallographic directions, will be discussed at more length in a subsequent paper.

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†Edgar Lewis Marston Fellow.

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SOME EFFECTS OF STRAIN IN THIN SPECIMENS ON ABSORPTION MEASUREMENTS AT LOW TEMPERATURE

G. G. Macfarlane, T. P. McLean,
J. E. Quarrington, and V. Roberts
Royal Radar Establishment,
Great Malvern, England
(Received February 16, 1959)

Direct transition excitons[1,2] and the magneto-optical effect[2,3] have recently been investigated in Ge by making transmission measurements on polished plates 10 microns and less in thickness, over the range from room temperature to 1.5°K under high spectral resolving power. We have already drawn attention[1] to discrepancies between our measurements and those of the Lincoln group,[3] which are much greater than the quoted limits of error. What we believe to be the explanation of these differences is now presented. It is emphasized that in order to get results which are accurately characteristic of the specimen, it must be mounted in a strain-free manner.

The discrepancies are twofold:

(a) At low temperatures the absorption line due to excitation of electrons into the ground state of the direct transition exciton is consistently observed by the Lincoln group at a higher energy than by us.

(b) The direct transition energy gaps E_0 deduced from the observations, which are in excellent agreement at room temperature,[4] diverge