Magnetoacoustic Open-Orbit Antiresonances in Copper*

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Antiresonances (sharp attenuation minima) have been observed in copper for shear acoustic waves propagating along [111] and for magnetic fields along [11$\bar{2}$] satisfying the resonance condition for open orbits along [1$\bar{1}$0]. The antiresonances give way to conventional resonances when the polarization vector $\vec{\epsilon}$ deviates from [11$\bar{2}$] by more than about 30°. We believe that the antiresonances are due to the so-called field force on the conduction electrons, whereas the resonances are due to the deformation force.

We report the experimental observation of magnetoacoustic open-orbit resonances (sharp attenuation minima) for shear waves in copper. This novel effect appears to be a manifestation of the so-called field force (due to the sound wave) on the conduction electrons, which is unusual in copper because the effective forces due to Fermi surface deformation have hitherto been assumed to be dominant.

Shear waves of frequency 168 MHz were propagated along the [111] axis of a single crystal of high purity copper (resistivity ratio about 20 000). For this geometry the two normal modes of sound propagation are degenerate, so that the polarization vector $\vec{\epsilon}$ can have any orientation in the [111] plane. Experimental difficulties due to internal conical refraction, in which the acoustic energy flux has a component normal to the propagation vector $\vec{q}$, were avoided by using a thin sample (1.4 mm). Under these conditions, the round-trip transit time for acoustic pulses is about 1.3 μsec, which is comparable to the pulse width (about 1.5 μsec), so that a certain amount of pulse overlap is unavoidable. However, we are inclined to rule out pulse interference effects as a possible complicating factor on the grounds that the estimated round-trip attenuation is so high (about 25 dB in zero magnetic field) that the first acoustic echo is negligible by comparison with the transmitted pulse. The latter was delayed several microseconds by passing it through a quartz rod, thus eliminating interference between it and the zero-delay electromagnetic leakage pulse.

If a magnetic field $\vec{H}$ is rotated in the (111) plane, open orbits are possible when $\vec{H}$ lies along [11$\bar{2}$] or equivalent directions. In $\vec{k}$ space the open orbit runs along [1$\bar{1}$0] and in real space it has a component along $\vec{q}$. This geometry is depicted in Fig. 1. Open-orbit resonances can occur whenever the spatial matching condition

$$\vec{q}\cdot\langle\vec{v}\rangle = n\omega_c \tag{1}$$

is satisfied, where $\langle\vec{v}\rangle$ and ω_c are the mean velocity and cyclotron frequency, respectively, of the open-orbit electrons, and n is an integer. In the present case (1) reduces to

$$H_n = \hbar c k_0 / e n \lambda, \tag{2}$$

where e/c is the electronic charge, λ is the sound wavelength, and k_0 is the open-orbit repeat distance, given by $4\sqrt{2}\,\pi/a$, with a the lattice constant.

The experimentally observed shear-wave attenuation versus magnetic field is illustrated in Fig. 2. The parameter Θ which distinguishes the five tracings is the angle between the polarization vector $\vec{\epsilon}$ and the magnetic field $\vec{H}$ and is estimated to be accurate to within about 2°. For $\Theta = 0$ strong antiresonances in the attenuation are seen

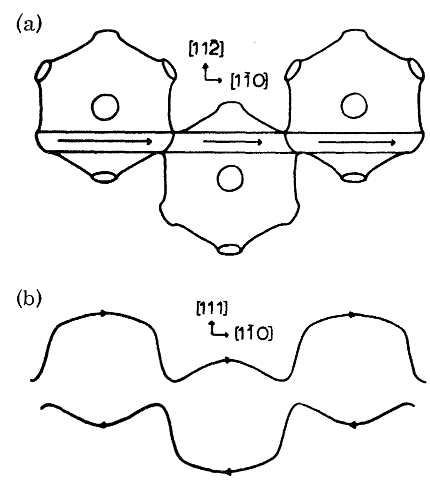

FIG. 1. (a) (111) projection of copper Fermi surface showing principal open orbit. (b) (11$\bar{2}$) projection of open orbit in $\vec{k}$ space, drawn to same scale.

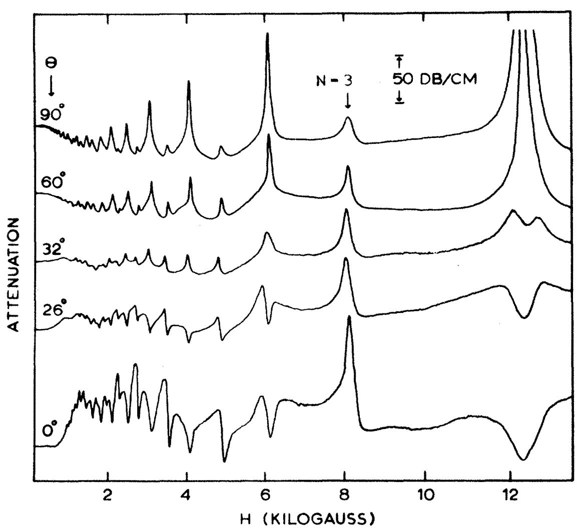

FIG. 2. Open-orbit resonances and antiresonances for 168-MHz shear waves propagating along [111] in copper. The angle **Θ** is the angle between the shear-wave polarization and the $[11\bar{2}]$ direction.

for all n up to about 17 except $n=1$ (not shown) and $n=3$, which give positive resonances. The antiresonances persist until Θ reaches about 30°, at which point they rather abruptly give way to positive resonances. We have selected two tracings in this neighborhood in order to illustrate the resonance line shape in the transition region. For larger values of Θ the resonances are all positive, the even harmonics being the strongest. The $n=1$ resonance would have occurred at $H=24.5$ kG, which was unattainable with our equipment; nevertheless we were able to obtain a good estimate of what the $n=1$ resonance would have been like by repeating some of the measurements at 75 MHz, for which the $n=1$ resonance occurs at a lower field. These data are not reproduced here because of the lack of detailed structure; however, we are able to report that the $n=1$ resonance was positive for all angles **Θ**, being largest for $\Theta=0$ and quite small for $\Theta=90°$. This behavior is similar to that shown by the $n=3$ resonance in Fig. 2. At sufficiently low fields the odd harmonics died out for all values of Θ and the even harmonics merged imperceptibly into the magnetoacoustic oscillations which would be expected from the calipering of the Fermi-surface belly, which has a dimension very close to one half of the open-orbit period.

Before discussing the possible mechanism of the antiresonances, we first point out that there seems to be no doubt that the observations are connected with the open orbits shown in Fig. 1. Both resonances and antiresonances occurred when the magnetic field $\vec{H}$ was located within about $1\frac{1}{2}°$ of the $[11\bar{2}]$ or equivalent directions; outside this range they were unobservable. The field values at which both resonances and antiresonances occurred satisfied (2) to within experimental error. No resonances or antiresonances were associated with the secondary open orbit which occurs when $\vec{H}\parallel[1\bar{1}0]$, probably on account of the very small width in $\vec{k}$ space of this orbit.

The interaction between acoustic waves and the conduction electrons in a metal has been considered in detail by Pippard.[2] In this analysis the effective force on the electron is broken down into two principal parts; the deformation force (associated with the deformation of the Fermi surface in the strain field due to the sound wave) and the field force (associated with the real electric fields which must be set up in order to establish the conditions of charge and current neutrality in the metal). In this paper general expressions were written down for the attenuation in a magnetic field, taking into account these two forces, but the open-orbit contribution was not considered explicitly, The characteristic resonance effect due to open-orbit electrons was predicted by Kaner, Peschanskii, and Privoroskii,[3] and the condition (1) is due to them. These authors recognized the existence of the field force but neglected it at an early stage in their calculation. The positive resonances which they predicted are thus associated primarily with the deformation force, and such resonances have been observed in copper by several workers.[4,5] More recently, Sievert[6] calculated the attenuation for a Fermi-surface model consisting of a set of overlapping cylinders, which permits open orbits if a small perturbing potential is assumed. The main purpose of this work was to investigate the effect of magnetic breakdown on the attenuation; however, the model did predict antiresonances for shear waves. It appears to us to be significant that Sievert's model was free-electron–like in that no deformation was assumed, i.e., the equilibrium form of the cylindrical Fermi surface under shear was taken to be the same as in the unstrained metal. The physical interpretation of the antiresonance is as follows: Since the electron current must be the same as the current in the lattice of positive ions, the electric field needed to maintain this current is inversely proportional to the conductivity. However, the magnetoconductivity undergoes a resonance when the condition (1) is satisfied: Hence the attenuation, which is roughly proportional to the electric field, shows an antiresonance.

We conclude from the foregoing that in a real metal the shear-wave attenuation would be expected to show resonances or antiresonances depending on which of the two types of force is predominant. If our interpretation is correct, the data shown in Fig. 2 can thus be thought of as a particularly direct demonstration of the existence of the two types of effective force in copper, a unique feature being that the relative contribution from the two forces can be varied at will simply by rotating the shear-wave polarization vector in the (111) plane. As far as we know, this is the first direct demonstration of the existence of the two types of force in a nonsuperconductor.[7]

Lastly, we mention some incomplete aspects of our work. One would of course like to be able to account in detail for the rich harmonic structure illustrated in Fig. 2 by reference to the specifics of the copper Fermi surface. At the present time, however, a proper theory of the resonance/antiresonance in the presence of both types of force is lacking. In this context it should be noted that Gavenda and Cox[5] have examined open orbits in copper with $\vec{q} \parallel [110]$. Several resonances were reported, but no antiresonances, and the authors interpreted their data in terms of the Fourier components of the electron velocity resolved along $\vec{\epsilon}$. Inasmuch as the quantity which enters the theoretical expression for the resonance amplitude is the product of the force and the velocity, this is tantamount to the assumption of a constant force. Taking both sets of data into consideration, it would seem possible to assert that in copper the deformation force usually predominates, but over the restricted domain shown in Fig. 2 it is weak enough to allow the field force to make its presence felt. In any realistic interpretation of the data, therefore, variations in the deformation force over the Fermi surface must be taken into consideration. This may not prove to be as difficult as it seems because, even though the absolute magnitude of the deformation force is difficult to estimate, its changes in sign are governed by powerful symmetry constraints. A more complete analysis along these lines will be presented at a later date.

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[1]P. C. Waterman, Phys. Rev. 113, 1240 (1959).

[2]A. B. Pippard, Proc. Roy. Soc., Ser. A 257, 165 (1960).

[3]E. A. Kaner, V. G. Peschanskii, and I. A. Privorotskii, Zh. Eksp. Teor. Fiz. 40, 214 (1961) [Sov. Phys. JETP 13, 147 (1961).

[4]C. W. Burmeister, D. B. Doan, and J. D. Gavenda, Phys. Lett. 7, 112 (1963).

[5]J. D. Gavenda and W. R. Cox, Phys. Rev. B 6, 4392 (1972).

[6]P. R. Sievert, Phys. Rev. 161, 637 (1967).

[7]For shear waves the field force is brought about by magnetic coupling to the ionic current, and is abruptly turned off below the superconducting transition, whereas the deformation force is unaffected. Related phenomena are discussed by J. R. Leibowitz, Phys. Rev. 136, A22 (1964).