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[1]S. Takagi, Acta Cryst. 15, 1311 (1962); J. Phys. Soc. Japan 26, 1239 (1969).

[2]A. Howie and Z. S. Basinski, Phil. Mag. 17, 1039 (1968).

[3]M. Wilkens, Phys. Status Solidi 6, 939 (1964).

[4]P. B. Hirsch, A. Howie, R. B. Nicholson, D. W. Pashley, and M. J. Whelan, *Electron Microscopy of Thin Crystals* (Butterworths, Washington, D.C., 1965).

[5]A. Howie and C. Sworn, Phil. Mag. 22, 861 (1970).

[6]R. B. Hammond, Department of Applied Physics, California Institute of Technology, 1971 (unpublished).

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Polarization Dependence of Shear-Wave Attenuation by Open-Orbit Electrons in Cu†

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The strength of measured resonant-attenuation peaks for ultrasonic shear waves caused by open-orbit electrons in Cu is shown to be related to the component of electron motion in the direction of sound polarization. The direction of the applied magnetic field is irrelevant except in determining the orbit geometry. The open orbit in Cu for $\vec{B} \parallel [101]$ has a much larger component of motion along $\vec{B}$ than perpendicular to it, so that interpretations of data based on motion in the plane perpendicular to $\vec{B}$ fail.

I. INTRODUCTION

It is usually stated[1] that magnetoacoustic resonances with shear waves are most pronounced when the external magnetic field $\vec{B}$ is perpendicular to the ultrasonic polarization vector $\vec{\epsilon}$. We report here a situation for which the open-orbit resonance is almost nonexistent for $\vec{B} \perp \vec{\epsilon}$. This observation not only sheds further light on the interaction responsible for the resonance, but it also illustrates the fallacy of ignoring electron motion along $\vec{B}$ in analyzing transport phenomena.

The open orbit which shows these anomalous effects arises for $\vec{B} \parallel [101]$ in Cu. It involves electrons lying on planes passing through the necks, as shown in Fig. 1. It has previously been observed with compressional waves.[2,3] We reported[3] a surprisingly large and rapid splitting of the fundamental resonance peak as $\vec{B}$ is rotated away from [101].

Figure 1 also shows the open orbit which runs along [111] for $\vec{B} \parallel [121]$. This is sometimes called the primary open orbit in Cu. It was the only one observed in the earlier magnetoacoustic experiments[4] using smaller values of ql. ($\vec{q}$ is the sound propagation vector and l is the electron mean free path.)

In this paper we compare the behavior of the resonances for the two open orbits as $\vec{B}$ is made parallel and perpendicular to $\vec{\epsilon}$. We call attention to the correlation between the orbit shapes and the amplitudes of the harmonics of the open-orbit resonances.

II. EXPERIMENTAL METHOD

The Cu specimen used in these experiments has a residual resistance ratio of about 35 000.[5] Its length in the direction of propagation is 1.25 cm. The specimen was mounted in a tiltable holder so that its axes could be precisely aligned in the magnetic field using the method described earlier.[6]

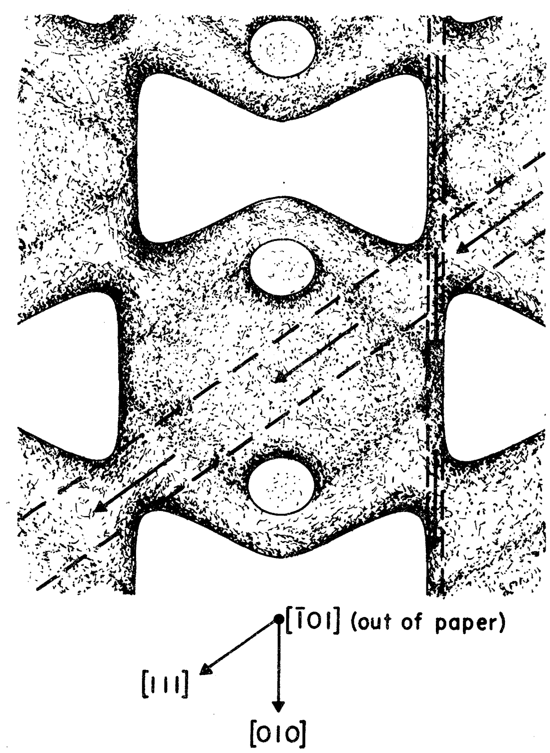

FIG. 1. Primary ([111] directed) and secondary ([010] directed) open orbits on the Cu Fermi surface (taken from Ref. 3).

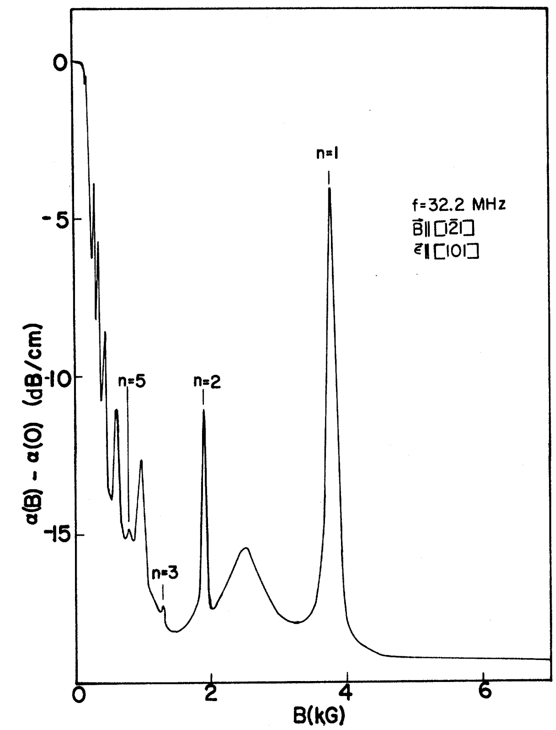

FIG. 2. Magnetic field dependence of the attenuation of 32.2-MHz slow shear waves in Cu propagating along $[\bar{1}01]$ with $\vec{B}$ oriented to give the primary open orbit. The fundamental and higher harmonics of the open-orbit resonance are indicated by $n=1,2,\ldots$.

A standard pulsed-carrier system, with 0.25-in.-diam 10-MHz fundamental-frequency transmitting and receiving transducers was used.

III. EXPERIMENTAL RESULTS

In all of these experiments the sound waves were propagated along $[\bar{1}01]$. There are two shear modes for this direction, a slower one with $\vec{\epsilon} \parallel [101]$ and a faster one with $\vec{\epsilon} \parallel [010]$. $\vec{B}$ was rotated in the $(\bar{1}01)$ plane so that it was always perpendicular to $\vec{q}$. When $\vec{B}$ is along $[1\bar{2}1]$ to give the primary open orbit, it makes angles of 54.7° and 35.3°, respectively, with the polarization vectors of the slow and fast modes.

A. Results for $\vec{B} \parallel [1\bar{2}1]$

Figure 2 shows the primary open-orbit resonance peaks for the slow mode. In addition to a sharply defined fundamental, harmonics up through the fifth are clearly evident. The resonance peaks for the fast mode are shown in Fig. 3. The height of the fundamental is somewhat smaller for the fast mode, about 9 dB/cm as compared with about 15 dB/cm for the slow mode. However, the attenuation should be inversely proportional to the velocity of the sound wave, so the relative heights can be explained largely by the fact that the fast wave has a velocity which is 1.78 times that of the slow wave.

Also shown in Fig. 3 is the change in shape and location of the resonance for the primary open orbit as $\vec{B}$ is rotated slightly away from $[1\bar{2}1]$ in the $(\bar{1}01)$ plane. For rotations less than 1° the change in location is negligible.

B. Results for $\vec{B} \parallel [1\bar{0}1]$

The secondary open-orbit electrons produce a very strong fundamental resonance in the attenua-

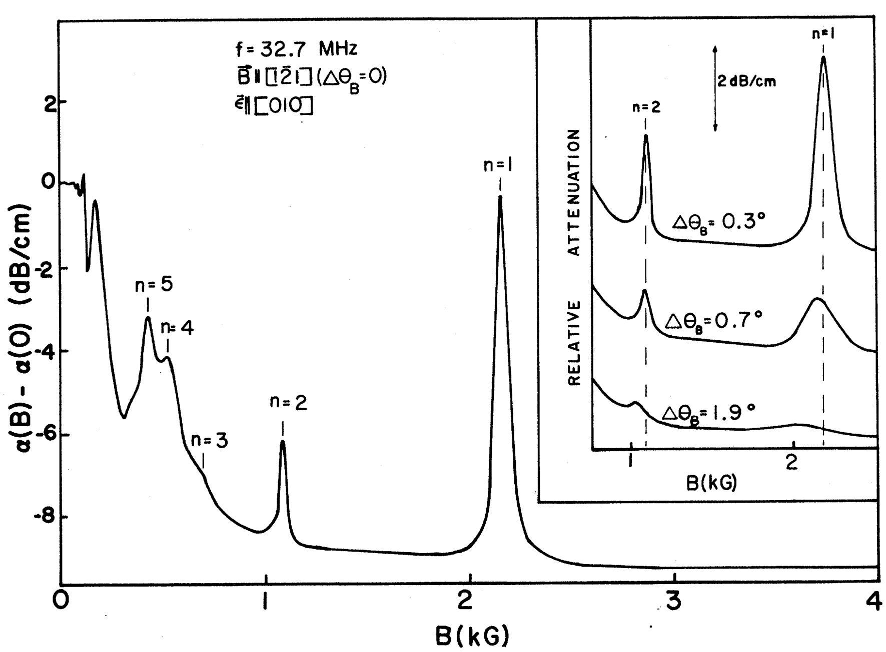

FIG. 3. Magnetic field dependence of the attenuation of fast shear waves in Cu, with $n=1,2\ldots$ designating the fundamental and higher harmonics of the primary open-orbit resonance. The inset shows the effect of rotating $\vec{B}$ away from $[1\bar{2}1]$ in the $(\bar{1}01)$ plane.

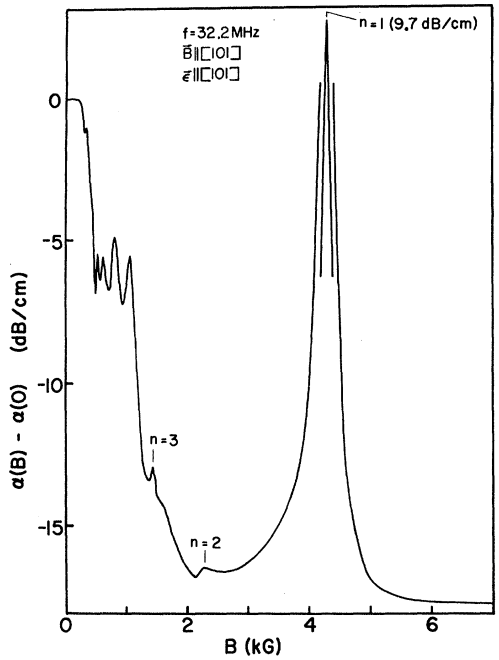

FIG. 4. Magnetic field dependence of the attenuation of slow shear waves in Cu with $\vec{B}$ oriented to give the secondary open orbit. Note that $\vec{B} \parallel \vec{\epsilon}$.

tion of shear waves with $\vec{\epsilon} \parallel [101]$, i.e., with $\vec{\epsilon} \parallel \vec{B}$, as shown in Fig. 4. Note the weakness of the higher harmonics. Figure 5 shows the rapid change in

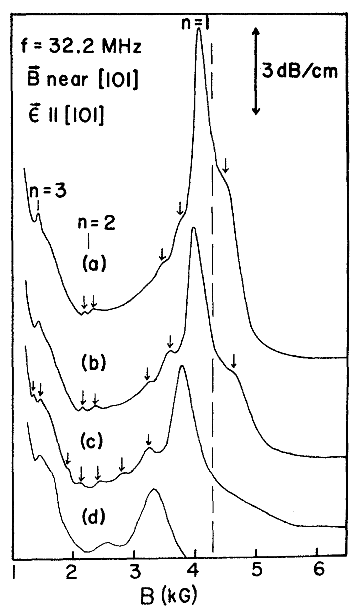

FIG. 5. Variation in secondary open-orbit resonance for the slow mode as $\vec{B}$ is rotated away from [101] in the $(\bar{1}01)$ plane by (a) 0.2°, (b) 0.3°, (c) 0.5°, and (d) 1.0°. The vertical dashed line indicates the location of the $n = 1$ peak for $\vec{B} \parallel [101]$. The short arrows mark the magnetoacoustic oscillations caused by extended orbits.

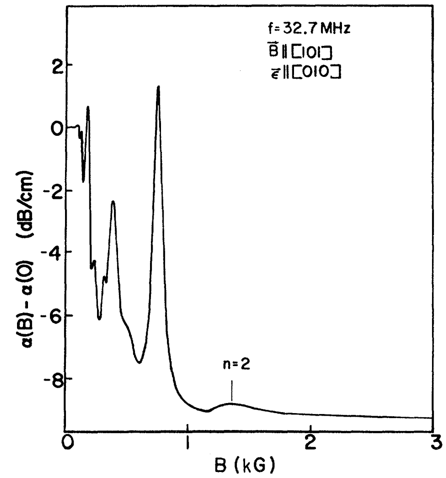

FIG. 6. Magnetic field dependence of the attenuation of fast shear waves in Cu with $\vec{B}$ oriented to give the secondary open orbit. The larger peaks are geometric oscillations from the dog's bone orbits. The bump labeled $n = 2$ is caused by the second harmonic component of the open orbit. Note that $\vec{B} \perp \vec{\epsilon}$.

position of the fundamental as $\vec{B}$ is rotated away from [101].

When $\vec{\epsilon}$ is perpendicular to $\vec{B}$, however, the fundamental resonance disappears and only a small bump is observed at the field corresponding to the second harmonic (Fig. 6). This is clearly contradictory to expectations that larger resonances always occur for $\vec{\epsilon} \perp \vec{B}$.

IV. INTERPRETATION

We must consider the motion of the electrons along $\vec{B}$ as well as in the plane perpendicular to $\vec{B}$, in order to be able to interpret these results. We will refer to these displacements as $s_{\parallel}$ and $s_{\perp}$, respectively. $s_{\perp}$ can be obtained in the usual fashion, i.e., by constructing cross sections of the Fermi surface in planes perpendicular to $\vec{B}$, scaling dimensions by $\hbar c/eB$, and rotating the resulting curve 90°. However, in order to find $s_{\parallel}$ we must integrate $v_{\vec{B}}$, the component of the Fermi velocity along $\vec{B}$, with respect to time. We use the gradient of Halse's function[7] describing the Cu Fermi surface for this purpose.

We find that a consistent interpretation of the open-orbit resonance harmonics can be obtained by considering the excursions of the electrons parallel to $\vec{\epsilon}$. As mentioned in Sec. III, pure shear modes propagate along $[\bar{1}01]$ only for $\vec{\epsilon} \parallel [101]$ and $\vec{\epsilon} \parallel [010]$. In order to observe the primary open orbit, we must have $\vec{B} \parallel [1\bar{2}1]$. For this situation, then, s_{101} and s_{010} each involve both $s_{\parallel}$ and $s_{\perp}$. Figure 7(a) shows the resulting s_{101} and s_{010} as functions of position along the direction of propagation. Figure 7(b) shows the same components of displace-

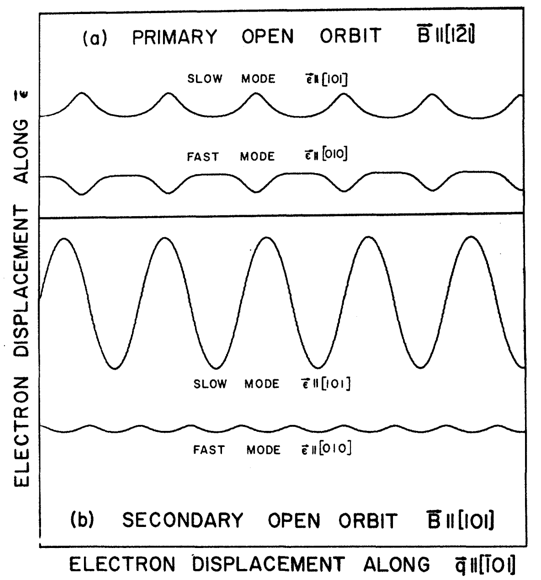

FIG. 7. Displacement of the electrons on open orbits in Cu resolved into components in the $\vec{\epsilon}$-$\vec{q}$ plane for both slow and fast modes. (a) Primary open orbit. (b) Secondary open orbit.

ment for the secondary open orbit ($\vec{B} \parallel [101]$).

The major features of the experimental results can be readily explained by reference to these figures. For the primary open orbit, Fig. 7(a) shows that the displacements along each polarization direction have approximately equal amplitudes, so one might expect the heights of the resonances to be equal (except for the effect of the different sound velocities mentioned earlier). On the other hand, Fig. 7(b) shows that amplitudes of electron displacement for the secondary open orbit are very different for the slow and fast modes. Contrary to the usual situation for extremal orbits, the displacement parallel to $\vec{B}$ is much larger than that perpendicular to $\vec{B}$. Furthermore, the period of the oscillation in s_{010} is one-half that of s_{101}, making it obvious why the $n=2$ resonance is observed, but not that for $n=1$.

The relative heights of the resonances are also explainable in terms of the orbit shapes. While the primary open orbit has higher harmonics in the displacements, the secondary open orbit appears to contain only a fundamental component. Apparently the heights of the resonances for $n>1$ are simply related to the Fourier components of the electron velocity along the direction of polarization. Pippard[8] has suggested a method for calculating the attenuation in terms of the Fourier components of the product of the effective force on the electrons and their velocities. In another paper[9] we present the results of calculations of open-orbit resonances for a simple phenomenological model using the Fourier components of the electron velocities only, and taking the effective force on the electrons to be simply proportional and parallel to the ion displacement.

V. SUMMARY AND CONCLUSIONS

The results for the [010] (secondary) open orbit in Cu underline the importance of considering all three components of the motion of conduction electrons in magnetic transport phenomena, not just those perpendicular to $\vec{B}$. For this particular open orbit the electrons execute much larger excursions along $\vec{B}$ than perpendicular to $\vec{B}$.

These results also give useful information about the direction and other characteristics of the effective force on conduction electrons in a sound field. Since the energy absorbed by the electrons is proportional to $\vec{F}\cdot\vec{v}$ integrated over a period of the motion, the fact that the principal features of the attenuation for open orbits are determined by the component of $\vec{v}$ along $\vec{\epsilon}$ implies that $\vec{F} \parallel \vec{\epsilon}$. Thus it follows that a shear ultrasonic wave is an effective electron-velocity-component analyzer.

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[1] M. H. Cohen, M. J. Harrison, and W. A. Harrison, Phys. Rev. 117, 937 (1960).

[2] G. N. Kamm, Phys. Rev. B 1, 554 (1970).

[3] W. R. Cox and J. D. Gavenda, Phys. Rev. B 3, 231 (1971).

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

[5] The specimen was cut from a boule obtained from A. F. Clark, Natl. Bur. Std., Boulder, Colo.

[6] W. R. Cox and J. D. Gavenda, Phys. Rev. B 3, 324 (1971).

[7] M. R. Halse, Phil. Trans. Roy. Soc. London A265, 507 (1969).

[8] A. B. Pippard, *The Dynamics of Conduction Electrons* (Gordon and Breach, New York, 1965), p. 126.

[9] J. D. Gavenda and M. E. Adah, Bull. Am. Phys. Soc. 17, 302 (1972). Complete results to be published elsewhere.