Quantum oscillations of the conductivity near the surface of bismuth

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Quantum oscillations have been observed experimentally in the derivative $\partial R / \partial E_n$, where R is the resistance of the bismuth sample, and E_n is the external electric field normal to the surface of the sample. Oscillations with two distinct periods have been observed. One agrees with the period of the Shubnikov-de Haas oscillations for electrons in the interior of the sample, and the other is $2.8 \pm 0.3\%$ shorter.

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Several theoretical studies have shown that the electron density within a distance on the order of λ_F (the electron wavelength at the Fermi level) from the surface of a conductor is different from its value in the interior (see Refs. 1 and 2, for example). (In bismuth, $\lambda_F \approx 100$–1000 Å.) The resulting charge causes an intrinsic distortion of the potential near the surface. We have now observed this distortion experimentally in a study of the quantum oscillations of the conductivity near a surface.

We used a field effect to study the conductivity near the surface of bismuth: the dependence of the resistance of the sample, R, on the component of the external electric field normal to the surface, E_n. For this purpose, one plane of the disk-shaped sample, 10 mm in diameter, was coated with an insulating film (SiO), on top of which a

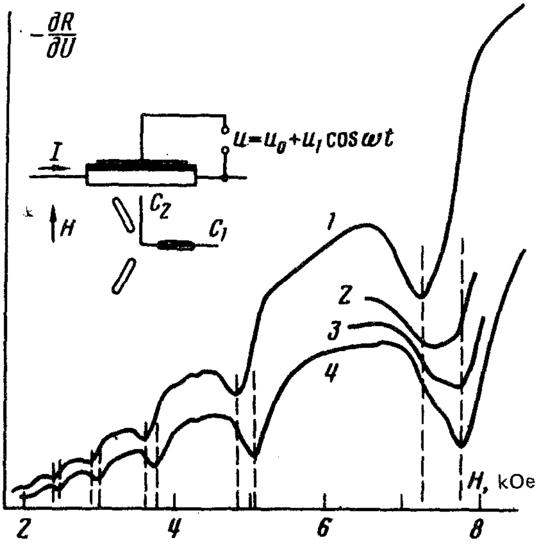

FIG. 1. The oscillations in $(\partial R/\partial U)H$. $\mathbf{H}\|\mathbf{N}\|C_2$, $T = 1.6$ K. 1—$U_0 = 65.3$ V; 2—$U_0 = -18.8$ V; 3—$U_0 = -37.4$ V; 4—$U_0 = -65.3$ V. The inset shows the experimental arrangement and the electron ellipsoids of the Fermi surface of bismuth.

metal film (Al) was deposited in a circle 5 mm in diameter. A voltage $U = U_0 + U_1 \cos \omega t$ was applied to the capacitor formed by the sample and a metal electrode. The normal field component E_n varied in proportion to U. Two contacts were applied at diametrically opposite points on the lateral surface of the sample and used to pass a direct current I through the sample. These contacts were also used to measure the voltage (see the inset in Fig. 1).

The voltage across the sample contains a constant component and also a variable component

$$V_\sim = I \frac{\partial R}{\partial U} U_1 \cos \omega t + \alpha R \omega C U_1 \sin \omega t.$$

Here C is the capacitance of the Bi–SiO–Al capacitor, $\alpha \sim 1$, and $R\omega C \ll 1$. The second term arises from the alternating current flowing through the sample through capacitance C. Phase detection yields a signal proportional to $\partial R/\partial U$. Since E_n is shielded at a depth $\lambda_D \sim 100$ Å in bismuth, the derivative $\partial R/\partial U \propto \partial R/\partial E_n$ is determined to a large extent by the electronic properties of the sample near the surface. The experimental procedure involved measuring the dependence of $\partial R/\partial U$ on a magnetic field H at various values of U_0.

For the measurements we used two samples, 0.4 and 1 mm thick, grown in a polished quartz form. The two samples had identically oriented crystallographic axes $C_2\|\mathbf{N}$, where $\mathbf{N}$ is the normal to the plane of the disk. The external magnetic field was imposed parallel to the normal in most of the measurements.

The modulation frequency $\omega/2\pi$ was 17 Hz. The ratio of the thickness of the SiO

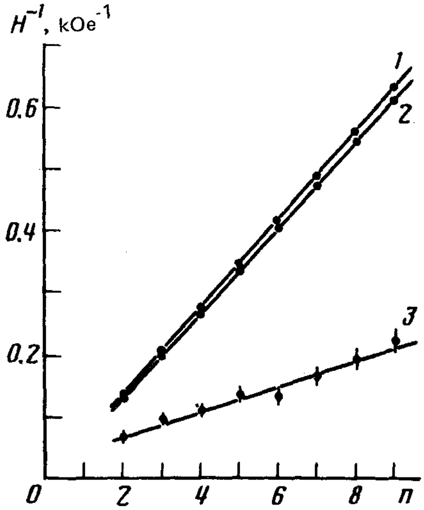

FIG. 2. Positions of the oscillation minima in the reciprocal field, H^{-1}, vs the index of the minimum (the points on the lines). 1—For the volume oscillation; 2—for the oscillation of $\partial R/\partial U$ at $U_0 = -65.3$ V; 3—the difference between 1 and 2, multiplied by 10.

film, d, to its dielectric function ϵ (determined from the capacitance C) was $d/\epsilon = 860$ Å.

The experimental results found for the two samples are the same. The field effect is weak: $(1/R)(\partial R/\partial U) \sim 3\times 10^{-7}$ V^{-1}. On the curves of $\partial R/\partial U$ vs H there are oscillations with two distinct periods (Fig. 1). When the voltage U_0 is positive (when the electrons are attracted toward the surface; see curve 1 in Fig. 1) the minima of the oscillatory part of $\partial R/\partial U$ coincide with the minima of the Shubnikov-de Haas oscillations in the interior of the sample. These oscillations are caused by two electron ellipsoids on the Fermi surface, which are tilted 30° from the normal to the surface of the sample. At negative voltages (curve 4 in Fig. 1) the minima of the oscillations are shifted to the right. These oscillations are also periodic in the reciprocal of the field (Fig. 2), but their period is $2.8 \pm 0.3\%$ shorter than that of the volume oscillations. The transition from the oscillation of one type to the other does not occur through a smooth displacement of the maxima upon a change of U_0 but through a gradual appearance of the minima with the new period (curves 2 and 3 in Fig. 1). The oscillation with the new period can be seen even at low, positive values of U_0. With decreasing U_0, the amplitude of this oscillation increases. The period of this oscillation is essentially independent of U_0, at least when it is the dominant oscillation (for U_0 from -40 to -80 V). As the angle between **N** and **H** changes, the oscillation with the new period behaves in a manner completely analogous to that of the oscillation caused by the electrons in the interior of the metal (Fig. 3): As the magnetic field is rotated in the C_1C_2 plane, the minima corresponding to low quantum numbers split. The relative magnitude of the splitting is the same for the two periods.

The existence of a quantum-oscillation period shorter than the volume period means that the Landau levels are shifted downward along the energy scale near the

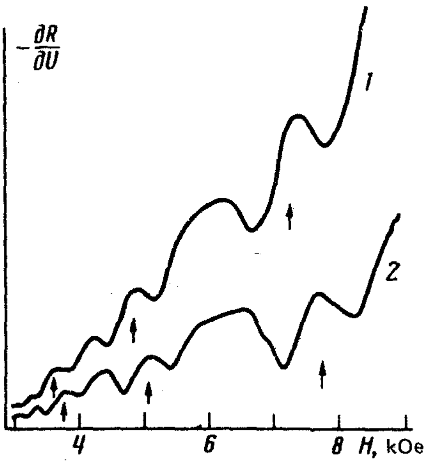

FIG. 3. The oscillation in $(\partial R/\partial U)H$ in an oblique magnetic field, $<\mathbf{H}$, $C_2 = 8°$, $T = 1, 6$ K. 1—$U_0 = 65.3$ V; 2—$U_0 = -65.3$ V.

surface, and there is a potential well for electrons near the surface. The fact that the oscillation period remains constant in the face of a marked change in amplitude indicates that the oscillation of the new period is related to the intrinsic potential relief near the surface, rather than the band curvatures which may result from an external electric field or from charges at the Bi–SiO interface. In principle, there are two possibilities. First, the new quantum-oscillation period may be related to the existence of a two-dimensional electron gas near the surface, localized in the potential well there, whose width does not exceed $\max(\lambda_F \lambda_D) \approx 1000$ Å. In this case, however, the orientation of the external magnetic field should act in different ways on the volume oscillation and the oscillation with the new period,[3] as long as the condition $\lambda_F < r$ holds (r is the radius of the electron orbit). The latter inequality clearly was satisfied in these experiments, so that the experiments with the oblique magnetic field rule out this first possibility.

Second, in the arrangement $\mathbf{H}\|C_2\|\mathbf{N}$ the orbital planes in coordinate space of the electrons at the extreme cross sections of the Fermi surface for two of the electron ellipsoids are inclined with respect to the surface of the sample. As the center of the orbit approaches the surface of the sample, therefore, part of the electron trajectory goes through the potential well. The result is a lowering of the energy of the Landau level near the surface. Surface states of this type, with a lowered Landau level, are apparently responsible for the oscillation with the new period. The reason why the new period is slightly different from the volume period is that the size of the orbit, $\sim r$, is far greater than the width of the well, $\sim \lambda_F$.

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