Determination of the dimensions of nonextremal Fermi-surface sections by transverse focusing of electrons

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A method is developed for the measurement of the parameters of Fermi-surface sections by focusing electrons in the metal using a transverse homogeneous magnetic field. The method is valid in the case of specular reflection of the electrons by the sample surface. The proposed method was used to reconstruct the intersection of the Fermi surface of bismuth with the bisector plane.

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A method is proposed here for the measurement of the diameters of nonextremal sections of the Fermi surface (FS) by electron focusing (EF) in a metal with a transverse homogeneous field.[1] The method can be used in the case of specular reflection of the electrons from the sample surface. The scheme of the experiment is the following: Two microscopic junctions, an emitter and a collector, are produced on the sample surface. Current is passed through the emitter and measurements are made of the voltage U on the collector as a function of the magnetic field H that lies in a plane perpendicular to the line joining the emitter and the collector and makes an angle ϕ with the sample surface. The idea of the use of EF is clear from Fig. 1, where the FS is shown in the form of an ellipsoid. The singularities of $U(H)$ are due to the effective electrons that acquire a momentum increment Δp in the emitter and reach the collector with this increment preserved.[2] In the considered geometry, the displacement of the effective electrons along the magnetic field is small during the time of motion from the emitter to the collector (the value of the displacement is determined by the dimensions of the microjunctions and by the distance L between the emitter and the collector. At $\phi = 0$, in a field H, the electrons reaching the collector come from the vicinity of the point d' such that the chord $dd' = eHL/c$, where d is a point symmetrical to d' on the FS (see Fig. 1), e is the electron charge, and c is the speed of light. The focusing takes place when dd' becomes equal to the extremal diameter A_2B_2', as confirmed by an exact calculation.[3] At $dd' \approx A_2B_2'$ the number of effective electrons is anomalously large. At $\phi \neq 0$ the situation of the focusing without reflections of the electrons from the sample surface is similar to the case $\phi = 0$, and focusing takes place when the chord aa' becomes equal to the extremal diameter A_1B_1 (see Fig. 1). The case of focusing in "multiple" fields at $\phi \neq 0$ easily reduces to the case of focusing without reflections from the surface, but at a different magnetic-field inclination angle. By way of example, we consider the focusing with a single reflection from the surface. In the case of specular reflection, the energy and the tangential quasimomentum are conserved,[4] so that upon reflection from the surface an electron from the point k on the FS jumps over to the point k', from A_1 to B_3', from A_2 to B_2', etc. In a field $\overline{\mathbf{H}}$, the electrons reaching the collector are from the vicinity of the point e' satisfying the condition $e'k + k'e = 2e'k = eHL/c$, where e is the point symmetrical to e' on the section $A_2'B_2$ (see Fig. 1). The effective electron moves over the FS from the point e' to the point k, jumps over from k to k' when reflected from the sample surface, and then moves over the FS to the point e. The point e' itself, in the vicinity of which the effective electrons are located, moves with increasing H over the section $A_2'B_2$ to the point B_2, just as in the field $\overline{\mathbf{H}}'$ directed perpendicular to the section $A_2'B_2$ in the case of focusing without reflections. Focusing without reflections in a field $\overline{\mathbf{H}}'$ will occur when $A_2B_2 = eH'L/c$. In the case of single reflection in a field $\mathbf{H}$, the focusing will occur when $A_2B_2 + A_2'B_2' = eHL/c$. For focusing with double reflection we have $A_1B_1 + A_3B_3 + A_3'B_3' = eHL/c$ etc. This makes it possible to determine the nonextremal dimensions A_2B_2, A_3B_3, etc.

The proposed method was used to reconstruct the intersection of the FS of bismuth with the plane passing through the axes C_1 and C_3. Bismuth was chosen because reflection of electrons in this material from a perfect surface perpendicular to C_3 is practically specular,[5] and the shape of its FS has been investigated in detail.[6] The plots of $U(H)$ are shown in Fig. 2. This figure illustrates well the characteristic features of EF in an oblique field. The following decrease with increasing inclination of the field: 1) the number of peaks, 2) the amplitude of the peak, 3) the ratio $(H^*_{n+1} - H^*_n)/H^*_1$ (n is an integer, $n-1$ is the number of reflections, H^*_n is the field of the n-th maximum of U),

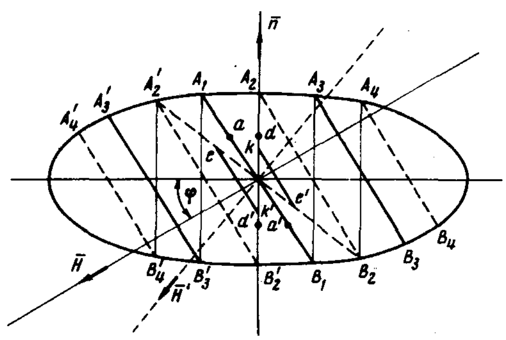

FIG. 1. Projection of Fermi ellipsoid and of the trajectories in it on the (n, H) plane, where **n** is the normal to the sample surface.

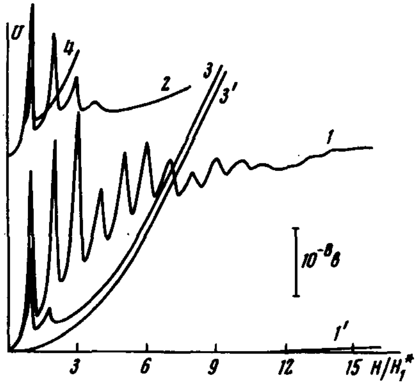

FIG. 2. Plot of $U(H/H_1^*)$ for various ϕ. For the curves 1(1′), 2, 3(3′), and 4 the values of ϕ are respectively 0, −68, −79, and 83 degrees. The abscissa axis shows the value of $-H/H_1^*$ for curves 1′ and 3′.

4) the difference between $U(H)$ and $U(-H)$. The decrease in the number of peaks and in the amplitude of the peak occurs for two reasons: 1) the number of focused electrons is decreased because $\partial v_{\parallel} \partial s$ is increased (s is the arc of the FS section shown in Fig. 2, and $v_{\parallel}$ is the velocity component along the sample surface), 2) the angle of entry of the electron into the collector is decreased. The decrease of the ratio $(H_{n+1}^* - H_n^*)/H_1^*$ is easily understood from Fig. 1. Attention is called to the appearance, in an oblique field, of a strong quadratic $U(H)$ dependence at directions of $\overline{\mathbf{H}}$ that exclude the entry of the electrons from the emitter into the collector. This monotonic dependence is due to the increase of the resistivity ρ of bismuth in a magnetic field. It is well known that $\rho \sim H^2$ in bismuth. In a field $\overline{\mathbf{H}}$ parallel to the surface, no such strong dependence is observed, owing to the shunting action of the surface layer, in which the electrons hopping over the surface as a result of the specular reflection from the surface have a large effective mean free path (the static skin effect[7]). The difference between $U(H)$ and $U(-H)$ is due to the fact that when the field is inverted the electrons reaching the collector from the emitter no longer have this possibility. In a strongly inclined field, the number of electrons multiply colliding with the surface and reaching the collector from the emitter is small, so that a difference between $U(H)$ and $U(-H)$ occurs in practice only in the vicinity of the first EF line, when the electron can arrive at the collector from the emitter without colliding with the surface.

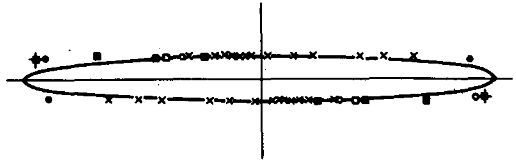

FIG. 3. Intersection of the FS and the bisector plane. The points marked ×, ●, ▪, ○, and □ are determined from the positions of the EF lines 1, 2, 3, 4, and 5, respectively. The measurement error is indicated for the extreme point (marked ▪).

Figure 3 shows a section through the Fermi surface of bismuth as reconstructed from EF measurements. As seen from Fig. 3, the aggregate of the diameters determined from the positions of the differently numbered EF lines forms a self-consistent system of points. The solid lines in Fig. 3 is an ellipse with semiaxis ratio 10 : 65.[6] The deviation of the FS section reconstructed on the basis of the EF from an ellipse is similar to that determined in[6].

[1]V. S. Tsoĭ, ZhETF Pis. Red. 19, 114 (1974) [JETP Lett. 19, 70 (1974)].
[2]Yu. V. Sharvin, Zh. Eksp. Teor. Fiz. 48, 984 (1965) [Sov. Phys. JETP **21**, 655 (1965)].
[3]S. A. Korzh, *ibid*. 68, 144 (1974) [**41**, 70 (1975)].
[4]A. F. Andreev, Usp. Fiz. Nauk **105**, 113 (1971) [Sov. Phys-Usp. **14**, 609 (1972)]
[5]V. S. Tsoĭ, Zh. Eksp. Teor. Fiz. 68, 1849 (1975) [Sov. Phys.-JETP **41**, (1975)].
[6]V. S. Édel'man, *ibid*. 64, 1734 (1973) [**37**, 875 (1973)].
[7]V. G. Peschanskiĭ and M. Ya. Azbel', *ibid*. 55, 1980 (1968) [**28**, 1045 (1969)].