Determination of non-extremal sections of equal-energy surfaces of arbitrary energy in bismuth films

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The areas of the non-extremal sections of the equal-energy surfaces having energies in the interval $0–2\epsilon_F$ were determined by the method of tunnel spectroscopy of size-quantized bismuth films.

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We present in this communication the results of measurements of the characteristics of a tunnel system containing a bismuth film in which size quantization and Landau quantization are realized simultaneously. The proposed procedure makes it possible to determine the areas of nonextremal sections of equal-energy surfaces of arbitrary energy in the investigated samples.

The gist of the observed phenomena consists in the following. It is known[1] that the energy spectrum of the electrons in a size-quantized film placed in a transverse quantizing magnetic field is fully discrete

$$\epsilon = \epsilon(n, l, s), \tag{1}$$

where ϵ is the electron energy, n is the dimensional quantum number, l is the orbital quantum number, and s is the spin number. Under these conditions, the electronic states that are allowed in quasi-momentum space are an aggregate of individual orbits, formed by intersection of the planes $p_z = \pi\hbar n/d$ allowed by size quantization, (z is the direction of the normal to the film and d is the film thickness) with the family of cylindrical surfaces allowed by the Landau quantization.

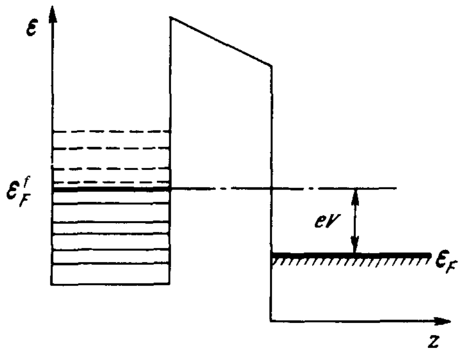

FIG. 1.

We consider next the level scheme of a tunnel system (Fig. 1) consisting of the investigated film, a thin dielectric gap, and a bulky metallic electrode. The current in this system should have singularities corresponding to discrete energy levels in the film. In particular, when the magnetic field H is varied and the voltage V on the tunnel junction is fixed, a singularity in the tunnel current will occur whenever the discrete level in the film coincides with a Fermi level of the bulky electrode or, equivalently, when an allowed orbit falls on equal-energy surface with energy $\epsilon = \epsilon_F^f + eV$ (ϵ_F^f is the Fermi energy in the film). The plot of $\partial I(H)/\partial V|_{V=\mathrm{const}}$ should contain in this case as many harmonics in the reciprocal magnetic field as there are size-effect subbands inside the indicated

TABLE I. Areas of nonextremal sections (10^{-42} $g^2\,cm^2\,sec^{-2}$) corresponding to different values of V and n, where V is the potential of the bismuth film relative to lead.

V, mV	$n = 1$	$n = 2$	$n = 3$	$n = 4$
- 17.5	0.8(± 10%)	–	–	–
- 16	1.3	–	–	–
- 13	2.1	–	–	–
- 10	4.2	0.67	–	–
- 6	6.2	2.2	–	–
- 5	6.7	2.9	–	–
0	8.5	6.5	1.7	–
1	8.6	6.4	2.1	–
5	12.0	8.3	4.5	–
10	14.2	11.1	6.3	2.0
12	16.6	11.1	8.3	3.1
15	16.7	15.3	12.5	5.0

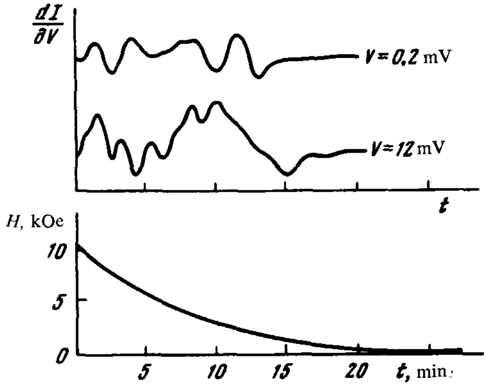

FIG. 2.

equal-energy surface. The period of each harmonic is determined by the area of the corresponding nonextremal section:

$$\Delta_n(H^{-1}) = \frac{2\pi e\hbar}{c\,S_n(\epsilon_F^f + eV, d)}. \quad (2)$$

We note that the considered phenomenon is similar to the well-known oscillations of the kinetic coefficients of a degenerate electron gas in a quantizing magnetic field, but subject to the important differences that, first, in our case the electrons that take part in the current belong to an arbitrary equal-energy surface (governed by the bias voltage on the sample) and, second, the current oscillations are determined by the nonextremal sections that are allowed by the size-quantization.[1)] The use of the described procedure for bulky samples makes it possible to determine the extremal sections of the equal-energy surface of arbitrary energy in the investigated material.

The results listed in Table I indicate the following: 1) the number of observed sections increases with increasing V (i.e., with increasing volume bounded by the equal-energy surface); 2) the area of each section increases with increasing V; 3) higher values of n (i.e., larger values of the transverse quasimomentum) correspond to sections with smaller area.

The experimental investigations were performed on systems consisting on a bismuth film, bismuth oxide, and lead. The bismuth films were mosaic single crystals oriented with the C_3 axis along the normal to the substrate. The procedure for obtaining such systems and their characteristics are described in[3]. The realization of the spatial quantization of the electron spectrum in the investigated films was monitored against the presence of size-effect oscillations of the differential current-voltage characteristic $\partial^2 I(V)/\partial^2 V$ in the absence of a magnetic field (see[3]). The measurements were performed at $T=4.2$ °K in the magnetic-field interval 0—15 kOe at bias voltages from -20 to 20 mV.

The functions $\partial I(H)/\partial V$ were measured for different values of V in samples containing Bi films 1100 Å thick. The corresponding curves are shown in Fig. 2. The obtained curves were reduced with a computer to determine the periods of the oscillations in the reciprocal magnetic field. From the values of the periods $\Delta_n(H^{-1})$ we calculated the areas of the nonextremal cross sections $s_n(\epsilon_F^f + eV)$ in the Bi films. The results of the calculations are listed in Table I.

[1)]The nonextremal sections of the Fermi surface in Bi films were determined with the aid of the Shubnikov—de Haas effect in our earlier papers.[2]

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