Observation of multichannel specular reflection of electrons from a tungsten surface

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Studies of the rf size effect on tungsten samples with a mirror-finish surface reveal lines due to cyclotron orbits which result from jumps of grazing electrons between sheets during multichannel specular reflection. These lines had been predicted previously by Peschanskiĭ and Yasemidis {V. G. Peschanskiĭ and K. Yasemidis, Fiz. Nizk. Temp. **6**, 541 (1980) [Sov. J. Low Temp. Phys. **6**, 260 (1980)]; V. G. Peschanskiĭ *et al.*, Zh. Eksp. Teor. Fiz. **80**, 1645 (1981) [Sov. Phys. JETP **53**, 849 (1981)]}.

In a weak magnetic field **B** directed parallel to a nearly mirror-finish surface of a metal, the anomalous skin effect is determined by grazing-incidence conduction electrons that collide with the surface at a small angle φ while conserving the tangential component of the wave vector, $\mathbf{k}_{\parallel} = \mathbf{k}_{\parallel}^{\text{rp}} \mp eB\delta/\hbar c$ (e is the electron charge, c is the velocity of light, $\hbar$ is Planck's constant, δ is the skin thickness, and the minus or plus sign is chosen depending on the sign of the curvature of a reference point with a

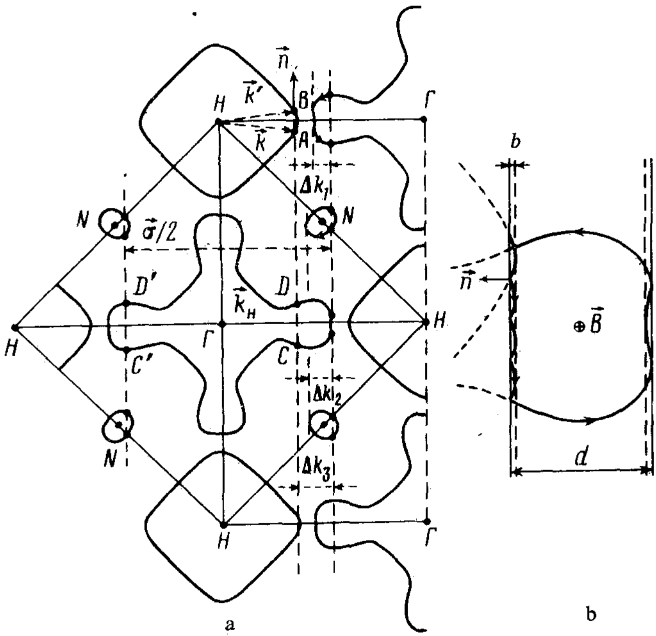

FIG. 1. a—Central cross section of the Fermi surface of tungsten[3] for $\mathbf{B} \parallel \langle 100 \rangle$; b—electron and hole paths in coordinate space.

radius-vector component $\mathbf{k}_{\parallel}^{\text{rp}}$ in a cross section of the Fermi surface). Such carriers correspond to, for example, grazing-incidence holes of an octahedron at H in tungsten[3] (Fig. 1) which have experienced reflections from A to B determined by the line $\mathbf{k}_{\parallel} = \text{const}$, parallel to the normal $\mathbf{n}$. Multichannel jumps are also possible,[4-8] e.g., from A to C, with a probability proportional to φ: $P_{AC} = \alpha_{AC}(\mathbf{k}_{\parallel})v_A(\mathbf{k}_{\parallel})v_C(\mathbf{k}_{\parallel}) = b_{AC}\varphi$ [$\alpha_{AC}(\mathbf{k}_{\parallel}) \neq 0$ depends on the wave functions of the electrons at A and C, while v_A and v_C are the normal components of the velocity at A and C, respectively].[7] Although P_{AC} is small, the probability for an escape from the skin layer over the transit time τ is not small, $b_{AC}\Omega\tau$, and it is independent of φ, since the rate of collisions with the surface, Ω/φ, is high (Ω is the cyclotron frequency).[2]

As they move from C along an electron orbit, the charge carriers which have acquired energy in the skin layer create a burst of an electromagnetic field in the interior of a plane-parallel plate of thickness d. When this field burst reaches the surface in the field $B_0 = \hbar\Delta k_{\parallel} c/ed$, a new rf-size-effect line appears. This line is determined by the extreme value of the difference $\Delta k_{\parallel} = k_{\parallel}^{e} - k_{\parallel}^{g}$ over all k_z. If we assume that the electron spheroid is slightly concave along ΓH, then there can also be rf-size-effect lines due to jumps of grazing electrons of the spheriod to the hole ellipsoid or to an ellipsoid in an adjacent Brillouin zone. It can be seen from Fig. 1 that there are several other possible scattering channels, but the corresponding rf-size-effect lines are superimposed on the rf-size-effect lines from cross sections with an extremum of the diameter $2k_F$ or corresponding chains of orbits. It thus becomes difficult to identify these lines.

Since the final state $k'_{\parallel} = \mathbf{k}_{\parallel} \pm \mathbf{g}$ is determined within a reciprocal-surface-lattice vector g (Refs. 5 and 8), the reflection from the (100) surface of tungsten may involve a change in $\mathbf{k}_{\parallel}$ by an amount equal to half the vector of the interior Brillouin zone, $\mathbf{g} = \mathbf{G}/2$, since this surface undergoes a reconstruction into a $c(2\times 2)$ structure at $T < 400$ K (Refs. 9 and 10). Analysis shows that this multichannel reflection is equivalent to that which has been discussed (Fig. 1).

The present experiments are carried out on the apparatus of Ref. 11 with tungsten samples prepared by a procedure similar to that of Ref. 3 from a single-crystal bar with a resistivity ratio $\rho_{300\,\mathrm{K}}/\rho_{4.2\,\mathrm{K}} \simeq 7\times 10^4$. The samples are immersed in liquid helium. The normal to the surface, **n**, is determined within $\pm 10'$ on a DRON-1 apparatus in a $\langle 100\rangle$ direction. After a chemical etching,[3] the sample is cemented with conducting cement to a tungsten ring and electro-polished in a 1% H_2O solution of NaOH. Over the B interval studied, the "specularity coefficient" p of these samples depends on φ and lies in the range $0.8 \geqslant p \geqslant 0.6$ (Refs. 12 and 13).

Figure 2 shows some representative recordings of the second derivative of the surface resistance with respect to the magnetic field, $\partial^2 R/\partial B^2$, for a sample with a mirror-finish surface and for the same sample after an additional grinding and chemical etching (a sample with a diffuse surface). The main rf-size-effect lines result from extremal orbits of the neck, x_1, and two cross sections of hole ellipsoids, d_4^0 and $d_{1,2}^0$, in accordance with Ref. 3.

The sample with the mirror-finish surface reveals two new lines, which have not been observed previously,[3] at fields of 19.6 and 36 G. Although the amplitudes of the ordinary rf-size-effect lines for the diffuse sample are roughly five times stronger, these new lines are not found for this sample. When a sample is held in air, these lines disappear. They also disappear when **B** is rotated a few degrees from $\langle 100\rangle$. A change in the frequency ω has no effect on the positions of the lines. It can be seen from Fig. 3 that in the case of a thinner sample, the new lines shift along with the main lines toward stronger fields as d is changed; these lines can therefore be regarded as size-effect lines.

The arrows in Fig. 2 show the positions expected for the rf-size-effect lines due to

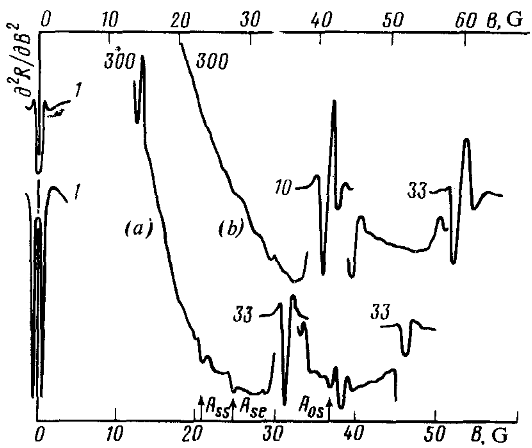

FIG. 2. The rf-size-effect lines for $\mathbf{B}\parallel\langle 100\rangle$, $T = 1.35$ K, and $\omega/2\pi = 2.7$ MHz from samples with a mirror finish (a; $d = 0.61$ mm, lower B scale) and with a diffuse finish (b; $d = 0.46$ mm, upper B scale).

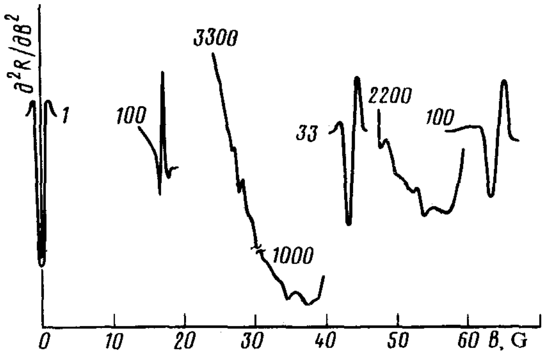

FIG. 3. The rf-size-effect lines of a tungsten sample with one mirror-finish side and one diffuse side for $\mathbf{B} \| \langle 100 \rangle$, $d = 0.43$ mm, $\omega/2\pi = 1.9$ MHz, and $T = 1.35$ K. The curve labels give the gain of the measuring instrument in comparison with the gain setting for the recording of the null line.

jumps of several types [spheroid-spheroid, A_{ss}; spheroid-ellipsoid, A_{se}; and (hole octahedron)-spheroid, A_{os}] according to calculations based on the dimensions of the Fermi surface from Ref. 3. The position of the A_{os} line agrees well with the observed result. The A_{se} line cannot be identified, since it coincides with a double chain of neck orbits ($2x_1$). There is some discrepancy in terms of the position of the A_{ss} line, apparently because of the concavity of the end of the spheroid along ΓH. The extent of this concavity is so slight (0.011 Å^{-1}) that it could not previously be determined.[3]

The ratio of the amplitudes of the jump lines and of the lines from the extremal cross sections is equal to b^2; we accordingly find the estimate $b_{os} \simeq 0.04$ and then $P_{os} = 0.005$. The small value of P_{os} is probably attributable to the fact that jumps have not been observed in experiments on electron focusing in tungsten.[14] There has been a report of the observation of intervalley jumps accompanied by changes in $\mathbf{k}_\|$ in bismuth by the same method and of an effect of the jumps on the magnetoresistance of tungsten.[8] This contradiction may be associated with the anisotropy of $\alpha_{ij}(\mathbf{k}_\|)$. We hope that future experiments on the rf size effect at various values of **B** and **n** are also with various surface states will make it possible to study the dependence $\alpha_{ij}(\mathbf{k}_\|)$.

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