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Angular dependence of the coefficient of specular reflection of bismuth electron from the binary plane

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We report further development of the method of determining the angular dependence of the coefficient q of specular reflection of electrons (V. S. Tsoi, Sov. Phys. JETP **41**, 927, 1975) on the basis of focusing the electrons with a transverse homogeneous magnetic field (V. S. Tsoi, JETP Lett. **19**, 70, 1974). The angular dependence of q is determined for the reflection of the conduction electron of bismuth from a plane perpendicular to C_2.

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INTRODUCTION

A method for determining the angular dependence of the specular reflection coefficient q was developed in[1] on the basis of electron focusing (EF) in metals by a transverse uniform magnetic field.[2] Also investigated was the dependence of q of bismuth electrons on the incidence angle θ in the case of reflection from the trigonal plane (plane perpendicular to C_3), and it was established that electron reflection from a perfect surface is practically specular ($q\approx 0.8$ at normal incidence). Even though an insignificant deviation (~5%) from the optimally chosen $q(\theta)$ dependence leads to a noticeable discrepancy with the experimental data, the small range of variation of $q(0.8-1.0)$ does not make it possible to establish with high accuracy the analytic form of the $q(\theta)$ dependence. The absence of a theoretical calculation of $q(\theta)$ for arbitrary θ permits a large leeway in the choice of the analytic form of $q(\theta)$.

In this communication we develop further the method of[1] for the measurement of $q(\theta)$ and measure the function $q(\theta)$ for bismuth electrons reflected from the binary plane (plane perpendicular to C_2), from which normally incident electrons are reflected practically diffusely ($q\approx 0.13$).

EXPERIMENT

The experimental setup for the observation of the EF is the following.[2] Two pinpoints are placed on a single-crystal metallic sample—an emitter and a collector. Current is passed through the emitter and the voltage U on the collector is measured as a function of the applied magnetic field **H**.

The samples were single-crystal bismuth disks of 10 mm diam and 2 mm thickness, with a specified crystallographic orientation, grown in a polished dismountable quartz mold.[3] The sample was cut from the seed crystal in such a way that a stub 5–10 mm long was left on the disk. The measurements were made on samples with two crystallographic orientations: 1) $C_3 \parallel \mathbf{n}$ and 2) $C_2 \parallel \mathbf{n}$ (**n** is the normal to the sample surface).

The construction of the measuring head is shown in Fig. 1. Sample 1 was placed on a copper disk 2, which was mounted on a rotating copper table 3 placed on needle supports 4. The sample was glued to the disk

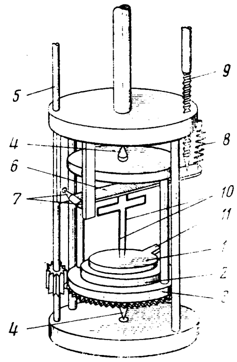

FIG. 1. Diagram of measurement head.

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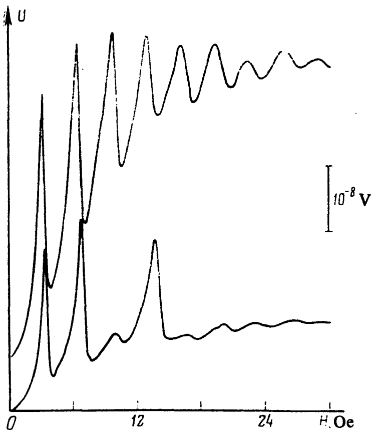

FIG. 2. Influence of local defect on $U(H)$ (see below text).

and the disk was glued to the table with BF-4 adhesive at several points on the perimeter. A reduction gear (not shown in the figure) was used to rotate the shaft 5, so that the table 3 could be rotated in controlled fashion in steps of several minutes of angle. The pins 10 were made of copper wire, usually of 0.1 mm diameter, and secured with BF-4 adhesive to a bar 6. The pinpoints were sharpened electrolytically. The bar 6 was fastened on needle supports 7. The position of the bar was adjusted through spring 8 by the position of the screw 9, the rotation of which made possible micrometric displacements of the pinpoints 10. The pinpoints were set along a given direction and on a definite section of the sample under a microscope. The instant when the pinpoint touched the sample was revealed by the appearance in the circuit of a 100-V battery, the positive terminal of which was connected to the pinpoint and the negative terminal, through a 10 Megohm resistor, to the sample. It was possible to pass through the emitter direct current, alternating sinusoidal current, and square-wave pulses with specified polarities and off-duty cycles. The work was performed at frequencies 10–100 Hz. The current leads were the emitter and a lead soldered to the copper disk 2. The voltage was measured between the collector and a wire soldered to the sample stub 11.

The magnetic field H was usually in the plane of the sample and was directed perpendicular to the line joining the emitter and the collector, in such a way that the trajectory of the electrons leaving the emitter was twisted towards the collector. The major semiaxis of one of the electron "ellipsoids" was also perpendicular to the emitter–collector line. Cases when the geometry was different will be specially pointed out. The distance L between contacts was 0.1–1.0 mm. The measurements were made in the temperature interval 1.3–4.2 K.

METHOD OF MEASUREMENT OF $q(\theta)$

Geometric model of electron focusing (GMEF). Even though the theory of EF has by now been developed, [4,5] the development of the GMEF is of definite interest for the following reasons. First, the application of the theory of[4,5] to the determination of $q(\theta)$ has not yet been developed; second, owing to the relative ease of determining $q(\theta)$ by GMEF; third, by using the GMEF it is possible to describe satisfactorily the available experimental data on EF.

The principal assumption made in the GMEF is that the quantity $U(H)$ (more accurately, the difference between $U(H)$ and $U(-H)$) is determined principally by the effective electrons which acquire in the emitter a momentum increment Δp and land on the collector with this increment preserved.[6] Besides the experiments noted in[1] evidence in favor of the GMEF is provided by the results of the following two experiments. Figure 2 shows plots of $U(H)$ for two cases. In one case the contacts are mounted on a perfect section of the sample surface (upper curve). In the second case (lower curve), the surface in the region between the contacts was locally spoiled by repeated placement of the copper pinpoint on this section. The distance from the defective surface section to the emitter was approximately one-third the distance between contacts. As seen from Fig. 2, the imperfection of the surface section from which are reflected the electrons focused after colliding twice with the boundary (third EF line) leads to a decrease of the amplitude of the corresponding EF by one order of magnitude, i.e., the value of q for normally incident electrons decreases by one order of magnitude. At the same time, the presence of a defective surface section between the contacts led to a substantial (by more than a factor of two) decrease of the ratio of the monotonic variation in a field ~30 Oe to the amplitude of the first EF line, formed by electrons that do not collide with the surface, and had practically no effect on the ratio of the amplitudes of the first and fourth EF lines. The decrease of the amplitudes of the fifth and higher-numbered EF lines is apparently due to the appreciable dimension of the defective section, which was comparable with the corresponding extremal dimension of the electron trajectory in the magnetic field for the observation of the fifth EF line. These singularities are in qualitative agreement with the conclusions of the GMEF.

The difference between $U(H)$ and $U(-H)$ in accord with the GMEF is due to the fact that when the field is inverted, such a possibility is now excluded for the electrons previously going from the emitter to the collector. It is easy to show, taking into account the kinematics of the specular reflection of the electrons,[7] that if H is perpendicular to the collector–emitter line and is inclined at an angle φ to the sample surface, the number of effective electrons experiencing multiple collisions with the surface decreases with increasing φ, and therefore, according to the GMEF, the difference between $U(H)$ and $U(-H)$ should decrease with increasing φ, as is illustrated in Fig. 3.[8] Figure 3 shows the results of measurements of the EF in an inclined field; curves 1′ and 3′ were obtained with the field direction reversed. At $\varphi = 0$ the difference between $U(H)$ and $U(-H)$ is large, and at $\varphi = 79°$ the difference takes place in practice in the vicinity of the first EF line, when the electrons from the emitter can reach the collector without colliding with the surface, and in the vicinity of the second EF lines (the angle φ is still not so large, and

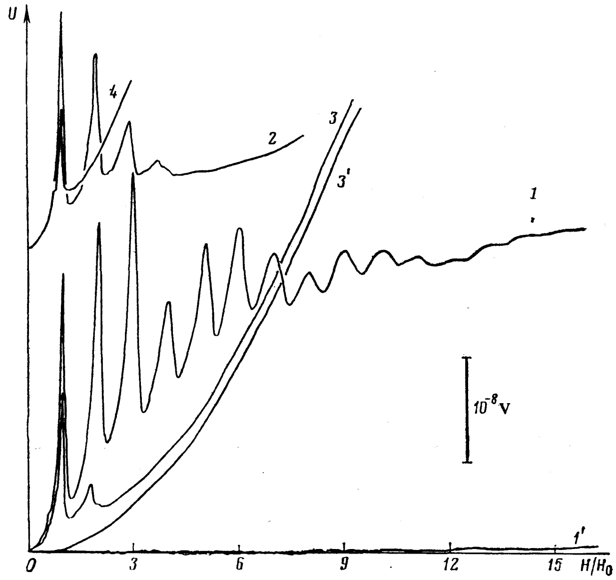

FIG. 3. *EF* in oblique field. Curves $1, 1' - \varphi = 0$; $2 - \varphi = -68°$; $3, 3' - \varphi = -79°$, $4 - \varphi = 83°$. $C_3 \parallel \mathbf{n}$, $T = 1.6$ K, $L = 0.3$ mm. The larmor radius at $H = H_0$ is $r_H = L/2$.

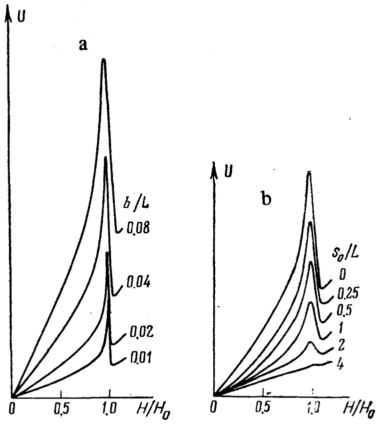

FIG. 5. a) Plots of $U(H/H_0)$ at different values of the parameter b/L; $q(\theta) \equiv 1$. b) Plot of $U(H/H_0)$ calculated according to the GMEF at different values of the parameter s_0/l ($s_0 = \pi L/2$ is the path length of the focused electron), $q(\theta) \equiv 1$.

there exists a small group of electrons focused by single reflection from the surface). With further increase of φ, the second EF line vanishes (curve 4). Attention is called to the onset, in an oblique field, of a quadratic dependence of both $U(H)$ and $U(-H)$, due apparently to the increased resistivity ρ of the bismuth in the magnetic field. It is known that for bismuth $\rho \propto H^2$. No such strong dependence was observed in a field **H** parallel to the surface, owing to the shunting action of the surface layer, in which the electrons hopping over the surface as a result of specular reflection by the surface have a large effective mean free path (the static skin effect[9]).

The general form of the function $U(H)$ is influenced, besides $q(\theta)$, by the finite electron mean free path l and by the value of the parameter b/L (b is the characteristic dimension of the contact). The influence of l is connected with the difference in the path length from the emitter to the collector, traversed by the different effective electrons. A similar phenomenon was observed in the study of the Gantmakher effect on potassium[10] and manifested itself in a change of the line shape with decreasing temperature (increasing l). The effect of l on $U(H)$ is illustrated in Fig. 4, which shows plots of $U(H)$ at various temperatures, and by Fig. 5b,

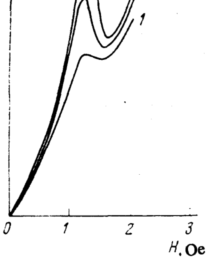

FIG. 4. Experimental plat of $U(H)$ curves 1—3 were plotted at sample temperatures 4.2, 3.2, and 1.6 K, respectively; $C_3 \parallel \mathbf{n}$, $L = 0.8$ mm.

which shows the results of calculations[1)] of $U(H)$ in accordance with the GMEF. In the calculations, the finite size of l was taken into account with the aid of a weighting factor $\exp(-s/l)$, where s is the path length of the effective electron ($q(\theta) \equiv 1$). An increase of l (see Figs. 4 and 5b) increases the ratio $\gamma = U^1_{max}/U^1_{min}$ (U^1_{max} and U^1_{min} are the values of $U(H)$ in the first maximum and the first minimum, respectively). The maximal γ is reached at $l = \infty$ and is determined by the parameter b/L (Fig. 5a). γ increases with decreasing b/L. The sharpness of the focusing can be determined with the aid of the "quality" of the EF line—the ratio of the width of the EF line at the 0.7 amplitude level to the value of the magnetic field at the maximum. It is significant that the "quality" of the EF line is practically independent of γ at $s_0/l \leq 4$ (see Fig. 5b), making it possible to use the GMEF to determine the parameter b/L from the experimental $U(H)$ dependence.

Attention is called to the large experimental value of γ (see, e.g., Fig. 2, $\gamma \simeq 5$) in comparison with that calculated by the GMEF at a given value of the "quality" of the EF line (see Fig. 5a). The value of γ calculated in accord with the model can be increased by taking into account the effectiveness of the angle of entry of the electrons into the collector. The collector voltage is proportional to the current flowing through the collector. Disregarding the structure of the microcontact, it is natural to assume that the current flowing through the collector has only a component perpendicular to the sample surface. Then the contribution of the effective electron to the normal current component is proportional to $\sin\theta$, where θ is the angle of entry of the effective electron into the collector.

In the present study the functions $U(H)$ (see Fig. 7a below, dashed curves) were calculated from formula (3) of[1] with appropriate changes to allow for the finite size of l and for the effectiveness of the electron entry angle into the collector.

Determination of the contact dimensions. In view of the importance of the parameter b/L, it is desirable to use the characteristic feature of the electronic "ellip-

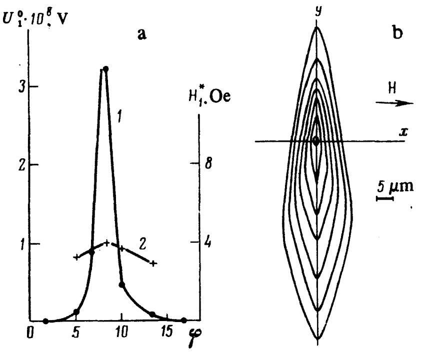

FIG. 6. Dependence of the quantities U_1^0(●) and H_1^*(+) on the direction of the line between contacts relative to the crystallographic axes of the sample, as determined by the angle φ; H is directed along C_1. b) Equipotential lines on the sample surface; the line between contacts is directed along C_2, the emitter is located on the negative semiaxis at a distance 0.25 mm from the origin, $H = 4$Oe; the ratio of the potentials of neighboring lines is 1.2. Experimental conditions: $C_3 \parallel n \perp H$, $L = 0.25$ mm, $T = 1.6$ K.

soid" of bismuth—its cylindrical shape in the region of the central section. For this reason, an appreciable number of electrons from the emitter is focused on a small section whose dimension b^* along the dimension of the major axis of the "ellipsoid" is approximately equal to the emitter dimension. By probing the structure of this section, it is possible to obtain information on the emitter dimensions. Technically it is relatively simple to perform the following experiment: mount the contact a distance L apart along different directions, and measure $U(H)$.

An unfavorable aspect of such a scheme is the possibility that the contact dimensions can change when the contact is repositioned. These changes, however, can be indirectly monitored against the width of the EF line and the value of the contact resistance.[6] Figure 6 shows the results of such an experiment, carried out using contacts of relatively large dimension. The direction of the contact line influences strongly both the amplitude U_1^0 of the first EF line (curve 1 on Fig. 6a) and the position of the first line in the scale of H (curve 2, H_1^* is the field of the first maximum). At $\varphi = \varphi_0 \approx 8°$ the line of the contacts is perpendicular to the major semiaxis of one of the electron "ellipsoids." We note that when the line of contacts is not perpendicular to the major axis of the electron "ellipsoid," then the only electrons that can reach the collector are those with an average velocity component along the direction of the major semiaxis. In this case the EF line is formed by electrons of a noncentral section, thereby decreasing strongly the amplitude of the EF line (see curve 1, Fig. 6a). However, the appreciable decrease of H_1^* with increasing $|\varphi - \varphi_0|$ is not due to focusing of the electrons of the sections of the Fermi surface, which differ noticeably in dimensions from the central section, but is connected with a condition imposed on the effective electrons, namely, during the time of motion from the emitter to the collector, the electron must negotiate a distance $\approx L\,\sin(\varphi - \varphi_0)$ along the field. Simple geometric calculation shows that this leads to a shift of the EF line into the region of weaker fields, and the position of the EF line in this geometry no longer determines the extremal dimension of the Fermi-surface section over which the effective electrons move.

Figure 6b shows the equipotential lines on the surface of the sample in the region of the segment on which the electrons of the central section of the "ellipsoid" are focused. The distribution of the potential along the radius drawn from the emitter was determined from the $U(H)$ dependence (the line shape) as the contacts were placed along this radius, and the distribution of the potential at a distance L from the emitter was measured in the experiment (Fig. 6a, curve 1). It is seen from Fig. 6 that EF on the sample surface produces a section of "high" voltage on the sample surface, approximately at the distance of the extremal diameter of the electron trajectory from the emitter in a direction perpendicular to the major semiaxis of the electron "ellipsoid." If we put $b^* = L\,\sin\Delta\varphi$, where $\Delta\varphi$ is the width of the U_1^0 line at the 0.5 level (Fig. 6a, curve 1), then b^* agrees within ~50% with the dimension b calculated from the EF line shape in accordance with the GMEF.

Conditions for the determination of $q(\theta)$. Let us formulate the conditions that are imposed on $q(\theta)$ by the characteristic singularities of $U(H)$ in the case of a pointlike emitter and a collector with dimension b. For extended emitters of small dimensions (compared with L) the conditions are practically the same. In the case of arbitrary $q(\theta)$, besides the decrease of the amplitude of the EF line with increasing number of the line, the distance between the lines and the field of the first EF line can also differ. An obvious illustration of these facts is the case of a stepwise $q(\theta)$ dependence ($q(\theta) = 1$ at $\theta \leq \theta_0$ and $q(\theta) = 0$ at $\theta_0 < \theta < \pi/2$[1]). We introduce the following notation: M and F are respectively the maximum and minimum incidence angles of the effective electrons that reach the collector without colliding with the boundary: $a = H/H_0$; a_{ext} and $2a_1$ are respectively the values of the field in the first and second maxima of $U(a)$ (let $a_1 \neq a_{ext}$); N_i is the number of electrons that execute i jumps, and $U_i(a)$ is their contribution to $U(a)$. Since[1]

$$N_i \sim \int_{F(a/i)}^{M(a/i)} q^{i-1}(\theta)\,d\theta,$$

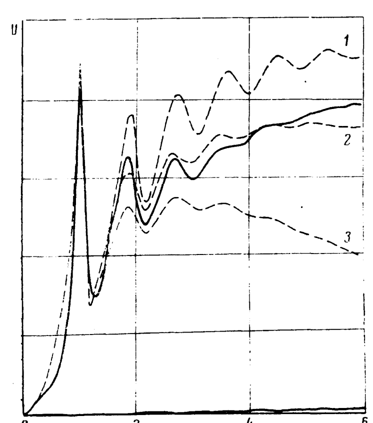

FIG. 7. Plot of $U(H)$.

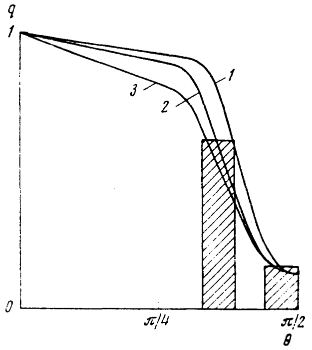

FIG. 8. Plot of $q(\theta)$.

it follows that (disregarding the effectiveness of the angle at which the electron reaches the collector and the fact that l is finite)

$$U_2(2a_1)/U_2(a_1)=\int_{F(a_1)}^{M(a_1)} q(\theta)\,d\theta/[M(a_1)-F(a_1)], \quad (1)$$

$$U_2(2a_{ext})/U_1(a_{ext})=\int_{F(a_{ext})}^{M(a_{ext})} q(\theta)\,d\theta/[M(a_{ext})-F(a_{ext})]. \quad (2)$$

It is easy to show that

$$\frac{\partial M}{\partial a}(a_1)\Big/\frac{\partial F}{\partial a}(a_1)=\frac{q(F(a_1))}{q(M(a_1))}. \quad (3)$$

The function $q(\theta)$ must also satisfy the conditions

$$0\leqslant q(\theta)\leqslant 1,\quad q(0)=1. \quad (4)$$

For the symmetrical case we have

$$q(\theta)=q(\pi-\theta), \quad (5)$$

and it is natural to require the satisfaction of the condition

$$q'(\pi/2)=0. \quad (6)$$

RESULTS

Measurements performed on a number of samples have shown that the general form of $U(H)$ depends very strongly on the crystallographic orientation of the surface from which the electrons are reflected. If $C_3 \parallel \mathbf{n}$, then the electron reflection is close to specular at all θ, and $U(H)$ takes the form of a set of equidistant spikes, with weakly attenuating amplitudes, superimposed on a smooth variation (see Fig. 2, upper curve, and Fig. 3, curve 1). The characteristic features of the behavior of $U(H)$ in the case $C_2 \parallel \mathbf{n}$ are illustrated in Fig. 7, where the plots of $U(H)$ are shown by solid lines (the lower curve was obtained with the direction of the magnetic field reversed). In this case the system of spikes attenuates strongly in amplitude with increasing number of the EF line, and the spikes are not equidistant. We note that samples with different crystallographic orientations were prepared by a single procedure. The sample orientation was set by the position of the seed crystal. The surface quality visually observed was the same in both cases.

Using the conditions formulated above (Eqs. (1)–(6)) we determined in accordance with the GMEF the form of $q(\theta)$ in the case $C_2 \parallel \mathbf{n}$ (curve 2, Fig. 8). The shaded areas in Fig. 8 are those that should lie under the $q(\theta)$ curve in the corresponding angle intervals (conditions (1) and (2)). The calculated $U(H)$ plots on Fig. 7 are shown dashed, and the parameter values $b/L=0.06$ and $L=0.15$ mm were used in the calculations. To illustrate the sensitivity of the calculated $U(H)$ to the form of $q(\theta)$ we used plots 1 and 3 of Fig. 8, respectively. The behavior of $q(\theta)$ is the same both in reflection from the trigonal plane and in reflection from the binary plane, namely, q first depends little on θ up to angles ~ 50–60°, and then decreases rapidly to the value $q(\pi/2)$. In the case of the trigonal plane, to approximate so steep a $q(\theta)$ dependence by a power series it sufficed to retain the terms of fourth or fifth power, but in the case of the binary plane it is necessary to retain in the series terms up to the tenth or eleventh power.

Attention is called to the strong crystallographic "anisotropy" of the quantity $q(\pi/2)$ (0.8 for the trigonal plane and 0.13 for the binary one).

DISCUSSION

Particular interest attaches to the weak dependence of q on θ in the angle interval 0 – ~ 60°, followed by the rapid decrease with increasing θ (for both the binary and trigonal plane). Allowance for the influence of the roughness of the boundary yields the following expression for q[7]:

$$q(\theta)=1-\alpha\sin\theta. \quad (7)$$

In the case of small groups of carriers with a quadratic spectrum, Eq. (7) is valid for arbitrary θ. It cannot be excluded that small deviations of the Fermi surface of bismuth from an ellipsoid[11] cause $q(\theta)$ to differ in form from (7). Formula (7), however, is valid in the general case for glancing electrons, so that the dimensions of the surface roughnesses can be determined from the $q(\theta)$ dependences in the region of small θ.[7] Estimates yield the following order-of-magnitude values of the roughness dimensions: ~ 10^{-8} cm for the trigonal plane and ~ 10^{-7} cm for the binary plane. We emphasize that the estimates are based on the assumption that the $q(\theta)$ dependence in the region of small angles is due to scattering by the roughnesses of the boundary.

Among the numerous possible causes of the observed behavior of $q(\theta)$, we wish to point out one[12] connected with the bending of the bands near the surface. The point is that the appearance of a negative surface charge prevents the electrons moving in the angle interval $0-\theta_c$ from reaching the surface, and causes them to be reflected from the potential barriers produced by the field of the surface charge. The value of θ_c is determined by the degree of bending of the bands: $\sin^2\theta_c = V/\varepsilon_F$[12] ($V$ is the magnitude of the bending of the bands and ε_F is the Fermi surface of the electrons), and for a qualitative agreement between the behavior of $q(\theta)$ and the proposed explanation the band bending should be $V\approx \varepsilon_F \approx 20$ meV. Favoring the presence of band bending near the surface in semimetals (antimony) is the radical difference between the reflection of the electrons (specular) and the holes (diffuse) from the sample surface.[13]

The presence of band bending near the surface causes formula (7) to underestimate the dimensions of surface roughnesses. In this case formula (7) must be modified:

$$q(\theta)=1-P(\theta)\alpha\sin\theta, \quad (8)$$

where $P(\theta)$ is the probability that the electron will "reach" the boundary. Owing to tunneling, the function $P(\theta)$ cannot be represented in the form $P(\theta)=0$ at $\theta<\theta_c$ and $P(\theta)=1$ at $\theta_c\leq\theta\leq\pi/2$. The roughnesses of the investigated surfaces, estimated on the basis of (8), exceed by one order the estimates obtained with formula (7), assuming that (8) is valid for arbitrary θ and that $P(\theta)\approx 1$ at large θ.

The diffuse reflection of normally incident electron from the binary plane and specular reflection from the trigonal plane may not be due to a difference between the scattering mechanisms, but only to the different dimensions of the surface roughnesses. It is known, for example, that different crystallographic planes can have different macroscopic roughnesses.

[1)]In the calculations of $U(H)$ the contact dimensions were assumed to be the same and the Fermi surface was assumed to be cylindrical.

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Nonlinear effects during the motion of vortices in superconductors

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The order parameter depends strongly on the coordinates in the mixed state in superconductors. A kinetic equation is derived in this case which describes the excitation-energy distribution function. This function varies strongly in a comparatively weak electric field E. At low temperatures, the effective electron temperature is proportional to $E^{2/5}$. If this temperature exceeds the energy gap, most of the energy of the stationary electric field should transform into energy of almost-monochromatic phonons. The boundary condition for the diffusion equation is obtained in the case of high impurity concentrations.

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INTRODUCTION

The energy relaxation time in metals $\tau_\varepsilon\sim\Theta_D^2/T^3$ is large at low temperatures. A large change in the electron energy distribution function therefore takes place in comparatively weak electric fields. In a normal metal, such a change has no effect on the conductivity. In a superconductor, the current density and the value of the energy gap are strongly dependent on the shape of the distribution function; therefore, departures from Ohm's law set in rather rapidly during motion of vortices. The significant change in the electron distribution function during motion of vortices can be observed from the spectrum of the emitted phonons. At sufficiently low temperatures and not too weak electric fields, almost all the energy of the electric field should transform into energy of monochromatic phonons with a frequency equal to 2Δ. In this case, the electron excitations are produced by the electric field at the center of the vortex, are accelerated to energy Δ, and then leave

