Electrical resistance of metallic microbridges with ballistic and quasiballistic electron transport

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(Submitted 24 July 1986)
Zh. Eksp. Teor. Fiz. **92**, 1026–1041 (March 1987)

The electrical properties of a novel object—microbridges, prepared from massive ultrapure metallic single crystals—are investigated at liquid helium temperatures. The original bulk crystals underwent a continuous transformation into microbridges devoid of structural defects. Pronounced nonlinearities on the current-voltage characteristics were observed which cannot be due to overheating of the microbridges. The influence of temperature and external magnetic fields on the electrical resistance of the microbridges was studied. A theoretical model is developed which describes how the electrons pass through the bridge when there are no bulk collisions. The model predicts that the resistance of the microbridges should deviate from the value given by the Sharvin formula for perfect microjunctions, as is observed experimentally. The influence of crystal lattice defects (dislocations, grain boundaries, impurity atoms) on the electric properties of the microbridges is analyzed, and it is found that the dislocations affect the resistance much more strongly than for massive specimens. Two new phenomena with a threshold dependence on the current density are found—electromigration of dislocations in microbridges not subjected to mechanical strain, and diode action of the grain boundary in bicrystal microbridges.

INTRODUCTION

Ballistic electron transport occurs in conductors whose length is much less than the mean free path of the electrons. In this case the kinetic properties of the conductor depend only on the acceleration of the electrons in the electric field and not on how they relax to equilibrium. The idea of experimentally fabricating extremely short metallic conductors was first proposed by Sharvin[1] and developed by Yanson.[2] In essence, the idea is to prepare a metal contact in an oxide layer sandwiched between two adjacent metals. Since the diameter of the contact is much greater than its length, the contact can be modeled as an infinitesimally thin dielectric barrier separating the two metals. When the electron mean free path is much greater than the dimensions of the contact, the contact resistance is determined by the velocity Δv gained in the electric field V near the contact; $\Delta v = eV/p_F$, where e and p_F are the charge and Fermi momentum of the electron. The contact resistance is then given by Sharvin's formula

$$R=(16/3\pi)p_F/ne^2d^2,$$

where n is the electron density and d is the contact diameter. This formula was later derived rigorously by Wexler[3] and refined by Kulik *et al.*[4]

The microcontacts were fabricated either by point welding or by extruding the metal into cracks in the oxide layer.[2] In either case, disruption of the crystal lattice and contamination of the metal by impurity atoms may be substantial near the contact, and it is therefore doubtful that ballistic transport of electrons can occur through such contacts. For example, in a later paper Sharvin and Bronev showed that the metal near the contact is deformed, as in a heavily loaded wire.[5] Khaĭkin *et al.*[6,7] reached the same conclusion by analyzing the nonlinearity of the resistance in metallic microcontacts. They attributed the anomalous behavior of the resistance to superconductivity induced by large deformations of the metal during the formation of the contact. However, there is an alternative point of view which holds that ballistic electron transport can occur in certain microcontacts.[2,8] Unfortunately, this point remains unclear because little is known regarding the contact dimensions and geometry or the state of the metal in the contact region. The only directly measurable dimension is the width of the oxide film, which gives an upper bound for the length of the contact. However, even these measurements should be approached with caution, because the film is not perfectly uniform and the exact site of breakdown is not known.

In view of the foregoing it will be of interest to analyze the electrical properties of microcontacts of specified shape when a direct method is used to control the density of crystal defects in the metal near the contact.

We have developed a nondestructive technique for fabricating a microcontact between two massive metal electrodes. In this method a large single crystal of highly pure metal is rigidly mounted in a holder and its diameter is decreased locally to form a narrow contact (microbridge) approximately 1 μm in diameter and 10 μm long (Fig. 1). The holder was designed to permit analysis of the dislocation structure of the microbridges under a JEM-1000 megavolt electron microscope. This enabled us to distinguish essentially dislocation-free bridges from ones containing dislocations and to analyze how structural defects (primarily dislocations) altered the electrical properties of the bridges. To our knowledge no experimental studies have previously been carried out along these lines. The chief difficulty here is to analyze the structure of the microbridges—chemical methods based on etching eat away the bridge, x-ray techniques are ruled out because no method is available for focusing the x-rays, and transmission electron spectroscopy is unsuitable because the substrate on which the microbridge is deposited is too thick. (By contrast, in our case there was no substrate

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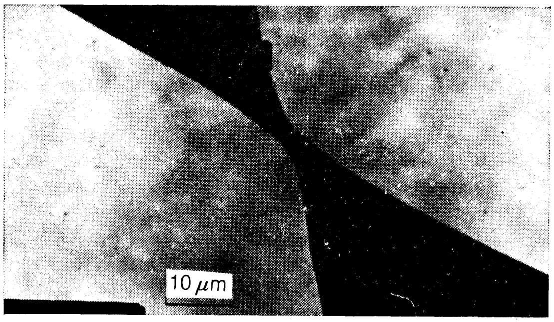

FIG. 1. Shadow photograph of a microbridge recorded using an electron microscope.

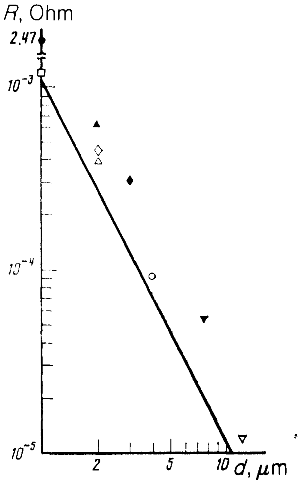

FIG. 2. Resistance of copper microbridges versus bridge diameter measured at the narrowest point. The dark geometric figures ●, ▲, ◆, and ▼ refer to specimens with axis along ⟨110⟩, while the light figures ○, △, ◇, and ▽ are for bridges with axis along ⟨111⟩. The straight line shows the resistance given by the Sharvin formula.

at all—our bridges were "suspended," i.e., they were supported solely by their side electrodes, so that we were able to analyze them by electron microscopy.) For this reason, data for massive specimens[9] has generally been cited to assess the role of defects (both dislocations and grain boundaries). The grain boundaries in a sputtered microbridge show up much more clearly than dislocations under an optical or electron microscope. Nevertheless, almost nothing is known about how grain boundaries alter the electrical properties of microbridges, although a great deal of work has been done for broad metal films.[10] In the extensive literature on metal microbridges, the influence of the structural defects is considered by dividing the bridges more or less arbitrarily into two groups, "clean" and "dirty," depending on whether the electron mean free path is greater than or less than the dimensions of the bridge.[11,12] This question is analyzed systematically in the present paper, apparently for the first time.

EXPERIMENTAL RESULTS

Although the microbridges were prepared from various metals, in most cases copper and tungsten were used. The tungsten specimens had axis parallel to the ⟨100⟩ direction, while most of the copper specimens had a ⟨111⟩ axis. The electric resistance was measured at 4.2 K to within 0.1% by the standard four-contact method (the contacts were soldered to the massive side electrodes of the microbridge). Control experiments demonstrated that the location of the contacts had no effect on the results of the measurements. Presumably, this was because the contact position affected only the resistance of the sides, and this change was small compared to the bridge resistance (less than 10^{-8} Ohm).

We first consider the electrical properties for bridges without defects. Numerous measurements revealed that the bridge resistance is always somewhat greater than predicted by Sharvin's formula (Fig. 2). The *I-V* characteristics of the microbridges are typically highly nonlinear and quite unlike the nearly linear *I-V* characteristics for microcontacts (Fig. 3). The first two jumps in the *I-V* curves (occurring at bridge voltages $\sim 10^{-3}$ and $\sim 10^{-2}$ V) are apparently not due to overheating. Indeed, the form of the *I-V* characteristics changed when the bridges were cooled by helium vapor or by using cold pipes. Direct visual observations failed to reveal any helium bubbles near the bridge, although it is well known that helium undergoes bubble boiling when a copper surface, say, is heated by 0.1–1 K (Ref. 13). On the other hand, measurements of the temperature dependence of the electrical resistance of the microbridges showed that heating by 0.1–1 K had no effect on the bridge resistance (see Fig. 4, which shows that the temperature dependence is of the usual type $R \propto T^3$). The third rise on the *I-V* characteristic (at a bridge voltage of ~ 0.1 V) is apparently due to heating of the bridge, since the helium was found to boil vigorously in this case. Unfortunately, we were unable to measure the temperature on the bridge surface more accurately because the surface was damaged or destroyed upon contact with a microthermometer. For the same reason, we were unable to connect miniature voltage leads directly to the thin neck connecting the two massive ends of the bridge.

The magnetoresistance of the microbridges also differed radically from the magnetoresistance for small metal wires (microcontacts, whiskers, microwires). For the latter, an external magnetic field starts to alter the resistance appreciably when the Larmor radius becomes comparable to the diameter of the wire.[14] For our microbridges, the influence of the field became significant at field strengths roughly 100 times weaker (Figs. 5,6) and the qualitative form of the *I-V* characteristic changed (Fig. 5). In addition, the magnetoresistance of the bridges was almost unaffected by the magnetic self-field of the current, which can reach several tens of oersteds (Figs. 3, 5), whereas the magnetoresistance of

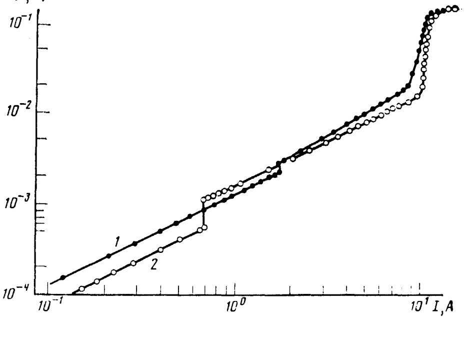

FIG. 3. *I-V* characteristics for copper (1) and tungsten (2) microbridges.

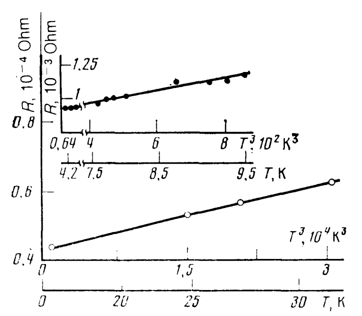

FIG. 4. Temperature dependence of the electrical resistance for copper microbridges.

wires and foils is very sensitive to the self-current.[15,16]

The electrical properties of the bridges changed markedly when defects (particularly dislocations) were introduced. The *I-V* curves for bridges with dislocations lacked the strong nonlinearity at bridge voltages of ~ 1 mV (Fig. 7) which was always present for dislocation-free bridges. In addition, their resistance was one or two orders of magnitude less than for bridges without dislocations. The average dislocation density in the bridges was 10^9 cm^{-2}, although the density in dislocation loops may have been somewhat higher (Fig. 8). The bridges dislocations were generated in a random manner (usually while the specimens were transported and mounted under the electron microscope). Only the tungsten bridges could be deformed in a controlled way. This was accomplished by exploiting the ponderomotive forces generated when a large current was passed through a bridge placed in a transverse magnetic field produced by a superconducting solenoid. The entire specimen (including the massive end electrodes as well as the bridge proper) was thus deformed with a radius of curvature of ≈ 1m, which sufficed to produce one or two dislocations.[17] Nevertheless, even a very small amount of deformation sufficed to completely suppress the nonlinearity of the *I-V* characteristic and more than double the bridge resistance (Fig. 9). For comparison, we note that the resistance of massive metal specimens remains practically unchanged under such a deformation.[17,18] The influence of the deformation on the magnetoresistance of the bridges was just as pronounced (Fig. 10). The introduction of dislocations greatly decreased the relative increment in the magnetoresistance, whereas the increment became larger in bulk crystals.[19]

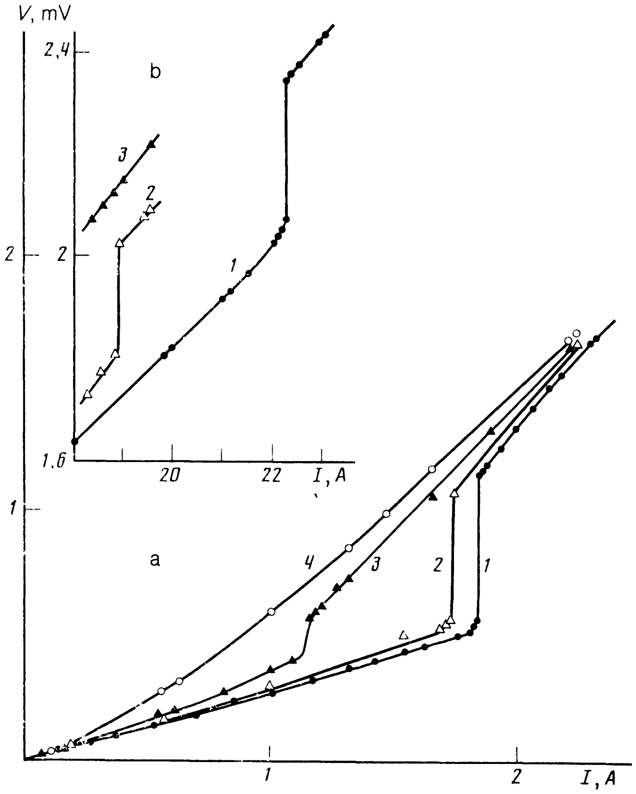

FIG. 5. Influence of a transverse magnetic field on the *I-V* characteristics of the microbridges: a) tungsten bridge, $H = 0$ (1), 20 Oe (2), 65 Oe (3), 162 Oe (4); b) copper bridge, $H = 0$ (1), 363 Oe (2), 462 Oe (3).

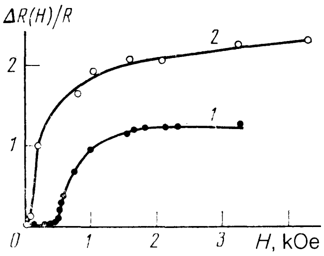

FIG. 6. Magnetoresistance of copper (1) and tungsten microbridges (2).

The behavior of the resistance R for the copper and tungsten bridges differed radically at high current densities ≈ 10^7 A/cm^2. For copper R decreased with time (Fig. 11), while for tungsten it remained constant (R was never observed to decrease for copper bridges not containing dislocations). This effect had a distinct current threshold and disappeared as soon as the current density dropped below the threshold value. The drop in R was not always continuous, and in a few cases R increased unexpectedly before continuing to drop. The temperature of the bridges (as deduced from helium bubbling) remained constant during these processes. The resistance of the bridges was found to be essentially unchanged in control experiments, in which the bridges were warmed to the boiling point of nitrogen and held there for a long time. We also carried out control experi-

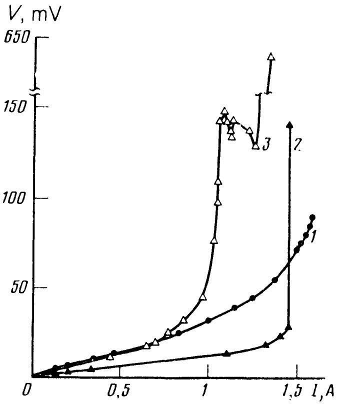

FIG. 7. *I-V* characteristics for microbridges containing dislocations: 1 and 2 give the *I-V* characteristic for a copper bridge before and after some of the dislocations were removed, respectively; 3 gives the *I-V* characteristic for a tungsten bridge.

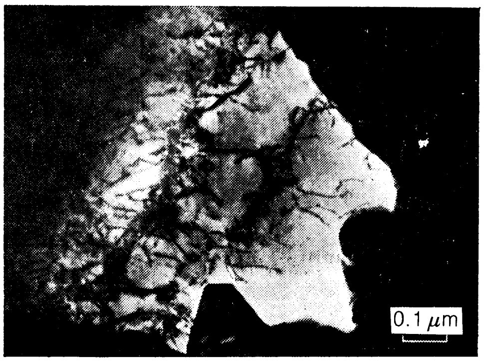

FIG. 8. Typical dislocation structure for microbridges deformed in a random manner.

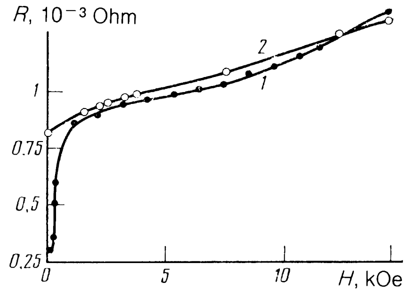

FIG. 10. Magnetoresistance of a tungsten bridge before (1) and after (2) a controlled deformation.

ments to verify that electrodiffusion of point defects had no effect on the resistance. This was done by introducing highly mobile point defects (H atoms, concentration 10^{-3}–10^{-4} at.%) into dislocation-free bridges. This increased the bridge resistance by 20–30%. When a current of 10^7 A/cm^2 was then passed through the bridges for 4 h, the bridge resistance remained unchanged to within 0.01% (the resistance returned to its initial value when the bridges were warmed).

The observed change in the resistance for bridges with dislocations must thus be due to migration of dislocations in response to electromechanical forces (unlike point defects, thermal activation is not required for dislocation mobility[20]).

Another type of threshold behavior was observed for copper bridges prepared from bicrystals (Fig. 12). At current densities $5\cdot 10^7$ A/cm^2, the bridge voltage and current began to depend on the polarity of the voltage, the difference reaching 20–25% (Fig. 13). Below this threshold, reversing the polarity changed the voltage and current by just 0.01–0.1%. The asymmetry of the current and voltage was much too great to be attributed to thermoelectric effects.[21]

At low currents the boundary separating the two crystallites had practically no influence on the resistance of the bridges, which was the same as for single-crystal bridges without defects. Nor did we observe any influence of the crystallite boundary on the resistance for massive specimens. Numerous measurements revealed that the residual resistance of the region of the specimen containing the boundary was exactly the same as for the single-crystal region (the scatter $\pm 5\cdot 10^{-12}$ Ohm·cm in the resistivities was probably due to variations in the impurity concentration in the specimen). This disagrees with previous work,[22–24] in which the boundary was found to alter the resistance appreciably. In that work the specimens were cut from recrystallized polycrystals containing large crystallite blocks. The boundary is known to sweep up and accumulate defects during the recrystallization process,[25] and it is likely that these rather than the boundary itself were responsible for the electron scattering. Our bicrystals were grown by the Czochralski technique on a double seed.[26] This method gives crystals with better quality and a dislocation-free boundary, which may explain why the boundary did not alter the resistance either for the massive crystals or for the microbridges.

We also studied the *I-V* characteristics for microbridges with defects in the massive ends as well as in the narrow central region. This was done by preparing the bridges from "dirty" metals with a resistance ratio $\gamma \approx 1000$. The *I-V* characteristics of these bridges remained linear even for currents high enough to burn them out.

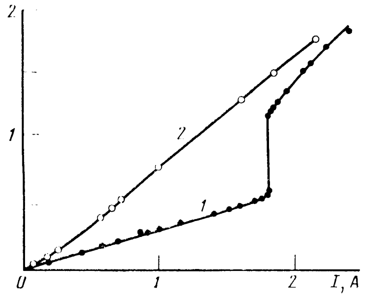

FIG. 9. *I-V* characteristic for a tungsten microbridge before (1) and after (2) a controlled deformation.

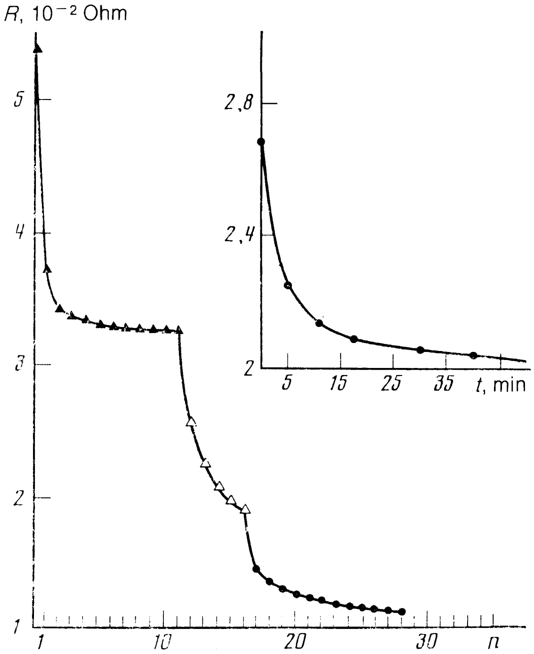

FIG. 11. Time dependence of the resistance of a copper bridge containing dislocations for above-threshold current densities. The top curve was recorded after the current had been flowing for a long time; the lower curve plots R versus the number of pulses, each of duration 1 s. ▲, $I = 1.468$ A; △, $I = 1.962$ A; ●, $I = 2.282$A.

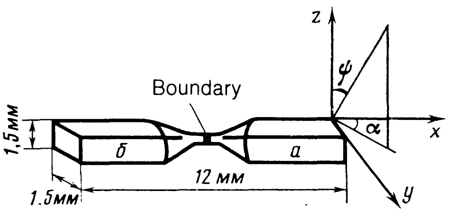

FIG. 12. Crystallographic orientation and dimensions of the bicrystal microbridges. Crystal *a*: [100] axis, $\alpha = 315°$, $\psi = 30°$; [010] axis, $\alpha = 34°$, $\psi = 80°$; [001] axis, $\alpha = 130°$, $\psi = 55°$. Crystal *b*: [100] axis, $\alpha = 305°$, $\psi = 50°$; [010] axis, $\alpha = 60°$, $\psi = 75°$; [001] axis, $\alpha = 165°$, $\psi = 45°$.

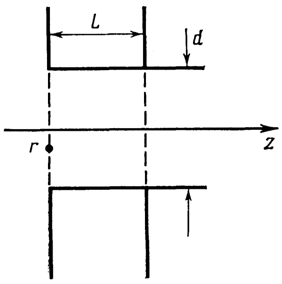

FIG. 14. Model of a microbridge.

DISCUSSION

It is convenient to discuss defect-free bridges first and then consider how structural defects change the electrical properties of the bridges.

In what follows we will discuss the three principal results obtained for defect-free bridges: 1) their failure to obey Sharvin's formula; 2) the nonlinearity of the *I-V* characteristic; 3) the unusual sensitivity of the bridge resistance to external magnetic fields.

To our knowledge, our present work is the first to directly test the Sharvin formula experimentally (Fig. 2). The departures from the formula cannot be due to errors in measuring the bridge diameter, because the latter was determined at high magnification under an electron microscope. The bridge resistance cannot have been increased by bulk collisions of the electrons, either, because the electron mean free path was two orders of magnitude greater than the length of the bridge. Moreover, the spatial dependence of the Sharvin resistance associated with the anisotropy of the Fermi surface[4] gives a correction of only a few percent for copper. Surface scattering of electrons thus remains as the only plausible explanation for the departure from Sharvin's formula during ballistic transport of electrons. It has been firmly established that metal surfaces reflect electrons almost specularly,[27] and that the surfaces themselves are composed of atomically smooth sections of area less than 100×100 Å (Ref. 28). Our bridge surfaces were probably bounded by atomically smooth planes of dimension much greater than the wavelength of the electrons. Single crystals always grow or dissolve along certain planes, and the faceting depends on the crystallographic orientation of the crystal.[29] It is possible that the bridge surfaces were also faceted differently, depending on their crystallographic orientation, and that this was responsible for the anisotropy in the resistance (Fig. 2). However, before we can establish the reason for the anisotropy, we must address the fundamental question of whether specular scattering (pseudoscattering in the terminology of Ref. 30) can increase the bridge resistance at all in the absence of bulk electron collisions.

Figure 14 shows a model microbridge consisting of a cylindrical channel of length L and diameter d. Because of bulk scattering, the mean free path l is $\gg L, d$. If ordinary (single-channel) specular reflection occurs on the channel surface, the channel has no effect on the resistance of the microbridge, which is the same as for a circular opening in a thin screen. This is because after entering the channel, an electron is reflected several times and then leaves the channel with probability one, reaching the opposite side of the screen regardless of the length of the channel. However, this will not always be the case if multichannel specular reflection[30] occurs at the surface of the channel. Indeed, Fig. 15 shows how backreflection can occur in this case. If at point 1 the momentum of an electron approaching the channel surface lies on the Fermi surface, then after reflection the momentum may again lie on the Fermi surface at the points 1′

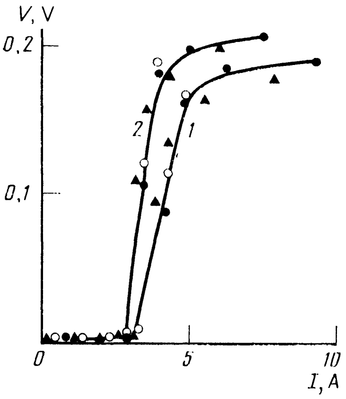

FIG. 13. *I-V* characteristics for some bicrystal microbridges: 1) crystal *b* at positive voltage; 2) crystal *a* at positive voltage. The geometric figures refer to different specimens.

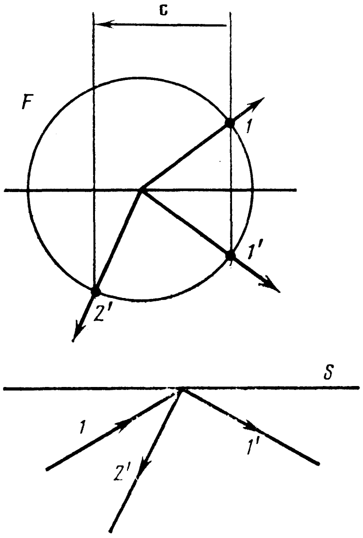

FIG. 15. Multichannel specular reflection. F denotes the Fermi surface, S is the crystal surface, and c is a reciprocal lattice vector.

and 2′. The electron energy is conserved by both of the transitions $1 \rightarrow 1'$, $1 \rightarrow 2'$, and the tangential component $\mathbf{p}_t$ is also conserved up to a reciprocal lattice vector $\mathbf{c}$ of the surface. The $1 \rightarrow 1'$ transition, which leaves $\mathbf{p}_t$ unchanged, is the normal process for surface scattering, while the Umklapp process $1 \rightarrow 2'$, is which $\mathbf{p}_t$ changes by $\mathbf{c}$, can lead to backscattering if $k_F < c < 2k_F$. There is thus a finite probability that an electron will emerge from the channel on the same side of the screen from which it entered.

The resistance of a microbridge, with allowance for backscattering at the channel surface, can be calculated readily using the following expression for the distribution function[31]:

$$f_{\mathbf{p}}(\mathbf{r}) = \alpha_{\mathbf{p}}^{+}(\mathbf{r}) f_0(\varepsilon_{\mathbf{p}} + e\varphi(\mathbf{r}) - e\varphi(+\infty)) + \alpha_{\mathbf{p}}^{-}(\mathbf{r}) f_0(\varepsilon_{\mathbf{p}} + e\varphi(\mathbf{r}) - e\varphi(-\infty)). \qquad (1)$$

Here f_0 is the equilibrium distribution; ϕ is the electrostatic potential $(e<0)$, and $\varphi(\pm\infty)$ is its value at $z = \pm\infty$; $\alpha_{\mathbf{p}}^{\pm}(\mathbf{r})$ is the probability for an electron originally at $z = \pm\infty$ to arrive at the point $\mathbf{r}$ with momentum $\mathbf{p}$. Clearly, $\alpha^{+} + \alpha^{-} = 1$. In what follows it will be convenient to regard $\alpha_{\mathbf{p}}^{\pm}(r)$ as the probability that an electron generated at $\mathbf{r}$ with momentum $-\mathbf{p}$ will move off to $z = \pm\infty$.

Let us calculate $\alpha_{\mathbf{p}}^{\pm}(r)$ for a point $\mathbf{r}$ at the entrance to the channel. If the initial momentum $\mathbf{p}$ is such that $(v_{\mathbf{p}})_z > 0$, then $(v_{-\mathbf{p}})_z < 0$ and an electron with momentum $-\mathbf{p}$ will definitely end up at $z = -\infty$. For this $\mathbf{p}$ we therefore have $\alpha^{-} = 1$ and $\alpha^{+} = 0$ at any point in the entrance to the channel. If now we take $\mathbf{p}$ so that $(v_{\mathbf{p}})_z < 0$, then $(v_{-\mathbf{p}})_z > 0$ and an electron with momentum $-\mathbf{p}$ at the entrance to the channel may end up at either $z = +\infty$ or $-\infty$. Writing $r_{\mathbf{p}}(\mathbf{r})$ and $t_{\mathbf{p}}(\mathbf{r})$ for the reflection and transmission amplitudes for an electron arriving with momentum $\mathbf{p}$ at point $\mathbf{r}$ at the entrance to the channel, we clearly have $\alpha_{\mathbf{p}}^{+}(\mathbf{r}) = |t_{\mathbf{p}}(\mathbf{r})|^2$ and $\alpha_{\mathbf{p}}^{-}(\mathbf{r}) = |r_{\mathbf{p}}(\mathbf{r})|^2$ if $(v_{\mathbf{p}})_z < 0$.

These results for $\alpha^{\pm}$ can be used to find the total current at the entrance to the channel. Expanding (1) in $e\varphi$, we obtain

$$J = Ve^2 N_F \int dA \langle v_z \theta(v_z) |t(r)|^2 \rangle. \qquad (2)$$

Here V is the potential difference between $z = +\infty$ and $z = -\infty$; N_F is the density of states at the Fermi level; the integration is over all points $\mathbf{r}$ in the entrance section; $\langle ... \rangle$ denotes an average over the Fermi surface; and $\theta(v_z)$ is the unit Heaviside function, equal to one for $v_z > 0$ and zero otherwise. This formula is essentially the same as the one derived in Ref. 32 for heterocontacts. However, it is important to stress that the amplitude $t(\mathbf{r})$ must be calculated quantum-mechanically, with allowance for the interference accompanying the multiple reflections from the channel walls.[33] A classical phase shift (for which pseudoscattering reduces to true scattering) occurs only in the massive ends of the bridge. The entire channel must therefore be treated as a single scattering entity. This becomes particularly clear when the channel dimensions d, L are comparable to the electron wavelength and states with a well-determined $\mathbf{p}$ exist only far from the channel, in the massive ends. The generalization of Eq. (2) to this case is

$$J = Ve^2 N_F \langle \theta(v_z) \sigma v \rangle. \qquad (3)$$

Here the effective cross section σ of the aperture depends on $\mathbf{p}$ and is defined as follows. Let a plane wave $\psi \propto e^{i\mathbf{pr}}$ with flux density I_0 (measured in electrons/cm^2·s) be incident on the aperture from $z = -\infty$. Then the Schrödinger equation determines ψ at $z = +\infty$, as well as the total transmitted flux P (electrons/s), and by definition $\sigma = P/I_0$. For 100% transmission in the channel ($t_{\mathbf{p}} = 1$), Eq. (2) gives the expression

$$\frac{J}{V} = e^2 N_F A \langle v_z \theta(v_z) \rangle \equiv R_0^{-1} = \left(\frac{\hbar^2}{e^2} \frac{16\pi}{k_F^2 d^2} \right)^{-1} \qquad (4)$$

for the Sharvin resistance. The resistance given by (2) can thus be rewritten as

$$V/J = R = R_0/\overline{|t|^2} = R_0 + R_0(1 - \overline{|t|^2})/\overline{|t|^2}. \qquad (5)$$

Here $\overline{|t|^2}$ is the transmission coefficient averaged over the Fermi surface and channel section. The second term on the right in (5) gives the contribution to the resistance from the backscattering and has the same form as the Landauer resistance.[34] We stress that if no phase shift occurs between successive reflections from the channel walls, the coefficient $\overline{|t|^2}$ differs completely from its value for ordinary diffuse scattering at the walls. In particular, it is independent of the channel length if $L \gg d$.

Multichannel specular scattering in copper has been demonstrated in experiments on electron focusing.[35] Different orientations of the microbridge correspond to different crystal faces at the surface, which have different multichannel scattering properties. This could account for the observed anisotropy in the resistance of copper microbridges with axes along ⟨111⟩ and ⟨110⟩ (Fig. 2).

The above arguments are valid only for low bridge voltages $eV \ll \hbar\omega_\theta$, where ω_θ is the Debye frequency, since otherwise the electron mean free path decreases rapidly as the electrons emit Debye phonons, and the bridge resistance increases abruptly. This apparently happens when the bridge voltage reaches $\sim 10^{-2}$ V (Fig. 3).

We next examine how electrons in the lens pockets of the Fermi surface influence the resistance of the bridges in the nonlinear region of the I-V characteristic. This influence has hitherto always been neglected in calculations of the resistance of microcontacts, because the electrons in the electron jack are much more numerous and were therefore assumed to dominate the resistance,[2,4,8] However, the simple qualitative arguments given below will show that for ballistic transport, the contribution from the lens pocket electrons may be comparable to the contribution from the electron jack. The lens pockets in the Fermi surface for copper and tungsten comprise roughly 10% of the total surface area.[36] However, the Fermi momentum of the pocket carriers is also roughly an order of magnitude less than for the main body of carriers (electron jack, hole octahedron).[36] The additional velocity gained by the pocket carriers upon free acceleration in the electric field is therefore an order of magnitude greater, so that their contribution to the current should be comparable to that for the electrons in the jack.

We believe the pocket electrons in the minor groups are responsible for the step in the bridge I-V characteristics at 1–2 mV (Figs. 3,6). For these voltages the pocket electrons gain a velocity $\Delta v = eV/p_i = (1.5\text{–}3) \cdot 10^5$ cm/s (where $p_i \approx 0.1\hbar k_F \approx 10^{-20}$ erg·s/cm), which is comparable to the speed of sound $s \approx 2.5 \cdot 10^5$ cm/s in copper and tungsten; they start to emit phonons spontaneously, which leads to electron scattering. The key fact here is that phonon emission, which is limited by the Pauli principle and by phase volume constraints, becomes allowed when the velocity Δv gained by the electrons exceeds the speed of sound. Rapid relaxation of the electron momentum then accompanies the emission of phonons with a maximum wave vector $q \approx 0.1\ k_F$. Ballistic transport of the pocket electrons thus breaks down at voltages 1–2 mV, and the bridge resistance rises rapidly.

The third nonlinear region on the I-V characteristic is due trivially to heating of the bridge; however, it seems odd that bridge burnout did not occur. Apparently, the hot electrons impinging on the massive cold end electrodes of the bridge give up their initial energy only very slowly. For the energy to relax many collisions are required: $\Delta\varepsilon/\hbar k_F s \gg 1$, and before significant deceleration occurs the electrons have already moved well away from the narrow neck at the center of the bridge. The massive electrodes thus remove heat rapidly from the bridge, preventing it from becoming hot. We note that no such marked nonlinearities were noted on the I-V characteristics for microcontacts consisting of normally conducting metals, and in fact they are probably unobservable. Because of the technique used to fabricate the microcontacts, their length did not exceed the thickness (10–100 Å) of the oxide layer. Phonon emission imposes a lower bound $v_F/\omega_\theta \approx 1000$ Å on the electron mean free path in the metal, where v_F is the velocity of the Fermi electrons. The current through the contact will thus remain qualitatively unchanged as the voltage increases, and in particular there can be no transition from ballistic to diffusion or thermal transport. Apparently, the electron transport mechanism through the contact also remains unchanged when a magnetic field or other external perturbation is applied. The resistance is found to change by only a few percent in fields 20–40 kOe, even for semimetal microcontacts.[37,38]

For microbridges, the effects of external magnetic fields are completely different, and very weak fields suffice to suppress the nonlinearity of the I-V characteristic completely (Fig. 5). It is very difficult to account for this even qualitatively. Probably the pocket electrons, whose Larmor radius is an order of magnitude less than for the electrons in the electron "jack", again play a dominant role here. The relative change in the resistance of a microscopic conductor in a magnetic field is known to be inversely proportional to the Larmor radius: $\Delta R_H/R \approx d/r$, where d is the diameter of the conductor and r is the Larmor radius.[14] In our case $\Delta R_H/R \gg d/r$ even if we take r equal to the Larmor radius for the electrons in the pockets. (For example, $\Delta R_H/R \approx 1$ at $H \approx 1$ kOe for copper and $H \approx 0.2$ kOe for tungsten, while for these H we have $d/r \approx 0.1$–0.2 (for tungsten, r is the Larmor radius of the carriers in the ellipsoidal and spheroidal pockets of the Fermi surface, while for copper it is the Larmor radius of the "neck" electrons in the narrow regions joining the regions of the Fermi surface containing most of the electrons). For bridges, in which bulk collisions of electrons are nearly absent, the bridge length L rather than its diameter should probably be taken as the characteristic dimension. The relation $\Delta R_H/R \approx L/r$ then closely describes the experimental results in magnetic fields too low to saturate the bridge resistance.

In addition to the external magnetic field, the very strong magnetic self-field of the current also acts on the electrons in the bridge. However, the effect on the resistance is some three to four orders of magnitude weaker than for an external field. Thus, a 1 kOe external field changes the relative resistance by 100%, while a self-field of 10 kOe changes it by just 0.1–1%. The effects of the magnetic self-field on the resistance of normal metals has been studied systematically only quite recently[39,40] (although the first work in this area was done long ago[41]), and it is difficult at present to judge how the bridge resistance should be affected. Indeed, the solenoidal self-field is strongest at the surface of the conductor and vanishes at the center. The action of the magnetic self-field on an electron which approaches the surface and is reflected by it will be exactly counterbalanced when the reflected electron arrives at the diametrically opposite point on the surface of the bridge (provided, of course, that the electron does not undergo any bulk collisions between reflections).

The resistance of the copper microbridges was unexpectedly sensitive to temperature (as well as to external magnetic fields). Of particular interest is the region $T < 10$ K, which was virtually unstudied in the microcontact experiments in Refs. 42–44. The bridge resistance increased by more than 20% upon warming to $T \approx 10$ K (Fig. 4), while the relaxation time via the electron-phonon collision channel is $\approx 10^{-8}$ s at this temperature,[45,46] This time is long compared to the 10^{-11} s required for the electrons to cross the bridge. In this case one should probably work with the electron scattering time rather than the relaxation time. This is also suggested by the temperature dependence $R \propto T^3$ of the resistance, which indicates that effective electron-phonon scattering occurred. The electron-phonon scattering time for the "neck" electrons in copper at 10 K is equal to $3 \cdot 10^{-11}$ s (Ref. 47); this is comparable to the electron transit time through the bridge and should increase the resistance appreciably.

Regarding the entire microbridge as a single scattering entity, we may thus state that the electrical resistance will change appreciably when the characteristic electron scattering length becomes comparable to the length of the bridge.

We will next discuss the electrical properties for bridges containing structural defects, beginning with the effects of dislocations on the resistance. The data obtained for massive specimens indicate that dislocations present to densities of 10^9 cm^{-2} should not alter the bridge resistance at all, because at these densities the relaxation time via electron-dislocation collisions is long (10^{-9}–10^{-10} s, Ref. 20) compared to the electron transit time 10^{-11} s through the bridge.

To explain the experimental findings we must postulate a transport scattering cross section of $\sim 10^3 a$ for each dislocation in the bridge, where a is the lattice parameter. In this case even a single dislocation can increase the bridge resistance significantly. The effect of the dislocations is pronounced because the electrons undergo multichannel specular reflection from the surface as they cross the bridge, i.e., the wave packet splits into pieces which interfere with one another upon reflection. Apparently, a single dislocation is enough to disrupt this "interference" state of the electrons, thereby increasing the resistance appreciably (Fig. 9).

The precise calculation of the contribution of a single dislocation to the bridge resistance should avoid the usual semiclassical approximations[48] and must consider the change in the electron transmission coefficient $t(\mathbf{r})$ caused by a single dislocation. Unfortunately, such a calculation remains beyond reach and our description is thus only qualitative. It is likely that just as for the case of phonons, one must work not with the transport cross section but with the total cross section 10^4a for electron scattering by a dislocation.[49] However, we stress that the quantity 10^3a does not correspond to the true transport cross section for the dislocation but reflects the combined scattering of electrons by the surface and by the dislocations. It therefore cannot be used to estimate the electromechanical forces acting on a dislocation.

According to theory, entrainment of dislocations by carriers and multiplication of dislocations in the electromechanical force field should occur at current densities 10^5–10^7 A/cm^2 (Refs. 50, 51). If we use the value $\sim 10^3a$ for the scattering cross section to calculate the threshold current density, we obtain 10^4–10^5 A/cm^2 for copper, [50,51] which is two or three orders of magnitude less than the experimental cross section. To remove this discrepancy, we must postulate a value $\sim a$ for the scattering cross section, i.e., take it to be comparable to the diameter of a dislocation core. The physical justification for this is clear—the carriers (electrons and holes) that transfer momentum most effectively to the dislocation are the ones that "impinge" directly on the core or else pass through its immediate vicinity.

Since the electrons and holes have opposite effects on a dislocation, the net electromechanical force in compensated metals like tungsten is relatively weak. This may explain why the resistance of the tungsten bridges does not change, although the high tensile strength of tungsten cannot be ruled out as an alternative explanation. In the copper bridges the resistance drops more than tenfold, but remains larger than for dislocation-free bridges (Figs. 7, 11). In this case the electron wind probably sweeps up only isolated dislocations and the dislocation clusters remain immobile (Fig. 8). Multiplication of dislocations in the clusters, where the electromechanical forces are strong, is probably responsible for the unexpectedly steep rise in the resistance, which runs counter to the general tendency to decrease continuously with time (Fig. 11). We emphasize that in this work we have for the first time observed the effects of electromechanical forces in specimens not subjected to an applied mechanical stress.[52]

The electrons in the lens pockets of the Fermi surface are the ones most affected by dislocations.[48] For instance, the scattering time for the "neck" electrons by dislocations in copper is an order of magnitude less than for electrons in the "jack" (Ref. 18). This apparently explains why the nonlinearity of the *I-V* characteristics associated with the pocket electrons is suppressed (Figs. 7, 9). Specifically, for ballistic transport the electrons in the pockets are the first to accelerate to supersonic velocities in the electric field. They begin to emit phonons vigorously, which in turn causes the resistance to rise abruptly so that the *I-V* characteristic becomes nonlinear. One may conjecture that because of the strong scattering by the dislocations, ballistic transport does not occur at all for the pocket electrons in bridges containing dislocations. This also explains why the resistance of deformed (i.e., dislocation-containing) bridges is so insensitive to external magnetic fields (Fig. 10); indeed, the field acts most strongly on the carriers in the pockets, and their contribution to the conductivity is severely curtailed due to scattering at dislocations.

We conclude by discussing how a grain boundary affects the electron transport through the bridge. The reason for the diode action of the boundary at current densities above the threshold $5\cdot 10^7$ A/cm^2 has not been identified, and indeed the mechanism for electron transport across a grain boundary is obscure.[53] Below the current threshold, the grain is probably nearly transparent to the electrons and merely bends rather than reflects the electron trajectories. Such refraction has been observed experimentally by exploiting the *rf* size effect in aluminum bicrystals.[54] Since the grain boundary has a regular structure,[25] the electron transmission through it should be coherent.[30] Coherent scattering of electrons *per se* does not contribute to the resistance.[30] We may therefore conclude that the grain-boundary resistance observed previously in Refs. 22–24 is due either to electron scattering at defects near the boundary or to a combination of scattering by both the boundary and the defects.

In closing we would like to thank V. N. Matveev for supplying the copper single and double crystals, S. V. Plyushchev for the tungsten single crystals, I. I. Khodos and his coworker V. G. Zharkov at the A. A. Baĭkov Institute of Metallurgy Acad. Sci. USSR for assistance with the electron microscope analysis, and V. A. Tulin and V. S. Édel'man for helpful consultations.

[1] Yu. A. Sharvin, Zh. Eksp. Teor. Fiz. **48**, 984 (1964) [Sov. Phys. JETP **21**, 655 (1965)].

[2] I. K. Yanson, Fiz. Nizk. Temp. **9**, 676 (1983) [Sov. J. Low. Temp. Phys. **9**, 343 (1983)].

[3] G. Wexler, Proc. Phys. Soc. **89**, 927 (1966).

[4] I. O. Kulik, A. N. Omel'yanchuk, and V. I. Shekhter, Fiz. Nizk. Temp. **3**, 1543 (1977) [Sov. J. Low. Temp. Phys. **3**, 740 (1977)].

[5] I. L. Bronevoĭ and Yu. V. Sharvin, in: Proc. 20th All-Union Conf. on Low Temp. Phys., Part 1, Moscow (1979), p. 140.

[6] M. S. Khaĭkin and I. Ya. Krasnopolin, Pis'ma Zh. Eksp. Teor. Fiz. **4**, 290 (1966) [JETP Lett. **4**, 196 (1966)].

[7] I. Ya. Krasnopolin and M. S. Khaĭkin, Pis'ma Zh. Eksp. Teor. Fiz. **6**, 633 (1967) [JETP Lett. **6**, 129 (1967)].

[8] A. G. Jansen, A. P. van Gelder, and P. Wyder, J. Phys. C. **13**, 6073 (1980).

[9] L. S. Palatnik, M. Ya. Fuks, and V. M. Kosevich, Mekhanizm Obrazovaniya i Substruktura Kondensirovannykh Plenok (Formation Mechanism and Substructure of Condensed Films), Nauka, Moscow (1972).

[10] Yu. F. Komnik, Fiz. Nizk. Temp. **8**, 115 (1982) [Sov. J. Low Temp. Phys. **8**, 57 (1982)].

[11] A. V. Zaĭtsev, Zh. Eksp. Teor. Fiz. **78**, 221 (1980) [Sov. Phys. JETP **51**, 111 (1980)].

[12] A. Barone, *Physics and Applications of the Josephson Effect*, Wiley, New York (1982).

[13] Yu. A. Kirichenko and K. V. Rusanov. Teploobmen v Gelii-1 v Usloviyakh Svobodnogo Dvizheniya (Heat Transfer in Helium-1 under Conditions of Free Motion), Naukova Dumka, Kiev (1983).

[14] Yu. P. Gaĭdukov, in: Élektrony Provodimosti (Conduction Electrons), M. I. Kagano and V. S. Édel'man eds., Nauka, Moscow (1985), p. 372.

[15] M. Yaqub and J. F. Cochran, Phys. Rev. Lett. **10**, 390 (1963).

[16] I. F. Voloshin, S. V. Kravchenko, N. A. Podlevskikh, and L. M. Fisher, Zh. Eksp. Teor. Fiz. **89**, 233 (1985) [Sov. Phys. JETP **62**, 126 (1985)].

[17] A. Yu. Kasumov, Ch. V. Kopetskiĭ, L. S. Kokhanchik, and V. N. Matveev, Fiz. Tverd. Tela **23**, 271 (1981) [Sov. Phys. Solid State **23**, 151 (1981)].

[18] V. F. Gantmakher, V. A. Gasparov, G. I. Kulesko, and V. N. Matveev, Zh. Eksp. Teor. Fiz. **63**, 1752 (1972) [Sov. Phys. JETP **36**, 925 (1972)].

[19] A. Pippard, in: *Physics of Metals*, Vol. 1 Electrons (R. Ziman ed.), Cambridge Univ. Press (1969).

[20] J. Friedel, *Dislocations*, Pergamon Press, Oxford (1964).

[21] I. F. Itskovich, I. O. Kulik, and R. I. Shekhter, Fiz. Nizk. Temp. **11**, 886 (1985) [Sov. J. Low. Temp. Phys. **11**, 488 (1985)].

[22] R. A. Brown, J. Phys. F **7**, 1477 (1977).

[23] B. N. Aleksandrov, Ya. S. Kan, and D. T. Tatishvili, Fiz. Met. Metalloved. **37**, 1150 (1974).

[24] T. I. Kulesko, Pis'ma Zh. Eksp. Teor. Fiz. **30**, 641 (1979) [JETP Lett. **30**, 607 (1979)].

[25] H. Gleiter and B. Chalmers, *High-Angle Grain Boundaries*, Pergamon (1972).

[26] H. F. Matare, *Defect Electronics in Semiconductors*, Wiley, New York (1971).

[27] V. S. Tsoĭ, in: Élektrony Provodimosti (Conduction Electrons), M. I. Kaganov and V. S. Édel'man eds., Nauka, Moscow (1985), p. 329.

[28] G. Binnig, H. Rohrer, C. Gerber, and E. Weibel, Phys. Rev. Lett. **49**, 57 (1982).

[29] R. Lowdiss and R. Parker, *Growth of Single Crystals*.

[30] V. F. Gantmakher and I. B. Levinson, Rasseyanie Nositeleĭ Toka v Metallakh i Poluprovodnikakh (Carrier Scattering in Metals and Semiconductors), Nauka, Moscow (1984).

[31] I. O. Kulik, R. I. Shekhter, and A. T. Shkorbatov, Zh. Eksp. Teor. Fiz. **81**, 2126 (1981) [Sov. Phys. JETP **54**, 1130 (1981)].

[32] R. I. Shekhter and I. O. Kulik, Fiz. Nizk. Temp. **9**, 46 (1983) [Sov. J. Low. Temp. Phys. **9**, 22 (1983)].

[33] A. A. Slutskin and A. M. Kadigrobov, Pis'ma Zh. Eksp. Teor. Fiz. **32**, 363 (1980) [JETP Lett. **32**, 338 (1980)].

[34] R. Landauer, Z. Phys. B. **21**, L47 (1975).

[35] S. I. Bozhko, I. F. Sveklo, and V. S. Tsoĭ, Pis'ma Zh. Eksp. Teor. Fiz. **40**, 480 (1984) [JETP Lett. **40**, 1313 (1984)].

[36] A. P. Cracknell and K. C. Wong, *The Fermi Surface; its Concept, Determination and Use in the Physics of Metals*, Oxford (1973).

[37] I. P. Krylov and Yu. V. Sharvin, Pis'ma Zh. Eksp. Teor. Fiz. **23**, 166 (1976) [JETP Lett. **23**, 146 (1976)].

[38] I. K. Yanson, N. N. Gribov, and O. I. Shklyarevskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **42**, 159 (1985) [JETP Lett. **42**, 195 (1985)].

[39] É. A. Kaner, N. M. Makarov, I. B. Snapiro, and V. A. Yampol'skiĭ, Zh. Eksp. Teor. Fiz. **87**, 2166 (1984) [Sov. Phys. JETP **60**, 1252 (1984)].

[40] É. A. Kaner, I. B. Snapiro, and V. A. Yampol'skiĭ, Fiz. Nizk. Temp. **11**, 477 (1985) [Sov. J. Low Temp. Phys. **11**, 259 (1985)].

[41] E. S. Borovik, Dokl. Akad. Nauk SSSR **91**, 771 (1953).

[42] A. P. Van Gelder, A. G. M. Jansen, and P. Wyder, Phys. Rev. B **22**, 1515 (1980).

[43] A. I. Akimenko, A. B. Verkin, N. M. Ponomarenko, and I. K. Yanson, Fiz. Nizk. Temp. **7**, 1076 (1981) [Sov. J. Low Temp. Phys. **7**, 524 (1981)].

[44] A. I. Akimenko, A. B. Verkin, N. M. Ponomarenko, and I. K. Yanson, Fiz. Nizk. Temp. **8**, 260 (1982) [Sov. J. Low Temp. Phys. **8**, 130 (1982)].

[45] A. Yu. Kasumov and V. N. Matveev, in: Proc. 20th All-Union Conf. Low Temp. Phys., Part 1, Moscow (1979), p. 154.

[46] E. R. Rumbo, J. Phys. F. **6**, 85 (1976).

[47] V. F. Gantmakher and V. A. Gasparov, Zh. Eksp. Teor. Fiz. **64**, 1712 (1973) [Sov. Phys. JETP **37**, 864 (1973)].

[48] J. M. Ziman, *Electrons and Phonons*, Clarendon Press, Oxford (1960).

[49] V. F. Gantmakher and V. T. Petrashov, in: Metally Vysokoĭ Chistoty (Highly Pure Metals), Ch. V. Kopetskiĭ ed., Nauka, Moscow (1976), p. 31.

[50] V. B. Fiks, Zh. Eksp. Teor. Fiz. **80**, 2313 (1981) [Sov. Phys. JETP **53**, 1209 (1981)].

[51] V. B. Fiks, Zh. Eksp. Teor. Fiz. **80**, 1539 (1981) [Sov. Phys. JETP **53**, 790 (1981)].

[52] V. I. Spitsyn and O. A. Troitskiĭ, Élektroplasticheskaya Deformatsiya Metallov (Plastic Deformation of Metals in Electric Fields), Nauka, Moscow (1985).

[53] M. I. Kaganov and V. B. Fiks, Zh. Eksp. Teor. Fiz. **73**, 753 (1977) [Sov. Phys. JETP **46**, 393 (1977)].

[54] Yu. V. Sharvin and D. Yu. Sharvin, Zh. Eksp. Teor. Fiz. **77**, 2153 (1979) [Sov. Phys. JETP **50**, 1033 (1979)].

Translated by A. Mason