Screening of surface roughness by an external electric field

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A technique has been developed for the direct observation of the effect of an electric field on the probability of specular reflection of electrons. Screening of surface roughness of bismuth by an external electric field during reflection from it of electrons has been observed.

When current carriers are reflected from the surface of a sample of a semimetal or semiconductor, screening of roughnesses by a surface charge field (near-surface bending of zones) can provide an efficient way of suppressing diffuse reflection. It is specifically this circumstance that underlies the radical difference in the probabilities of specular reflection of electrons $q_e=0.8$ and holes $q_h=0.2$ upon reflection from the same part of surface of a sample of antimony, observed in Ref. 2 with the help of transverse electron focusing (EF).[3] Of special interest is the solution of the problem of controllable variation of the reflection by artificial bending of zones.

When an electron is reflected from a surface, it undergoes either intravalley or intervalley scattering. Intervalley scattering is the main cause of the suppression of intravalley specular reflection.[4] The efficiency of intervalley scattering in bismuth is determined by roughnesses of atomic scale. Since the Debye screening radius in bismuth $r_D \sim 200$ Å, much smaller than the interatomic distance, screening of a roughness of atomic scale by a surface charge field should virtually eliminate intervalley scattering, thereby significantly increasing the probability of intravalley specular reflection.

In the present letter, we report the results of an experimental study of reflection of electrons from a surface with the help of EF. We used the ordinary measurement setup:[3] two point contacts—an emitter and a collector—were mounted on the surface of a single-crystal sample of bismuth with surface normal of the sample $\mathbf{n} \| C_3$. Nonequilibrium electrons were injected into the sample through the emitter, and an electric current was passed through the contact. The voltage at the collector U_k was measured as a function of the intensity of a magnetic field **H** lying in the plane of the surface of the sample and directed perpendicular to the line between the contacts which passed through the emitter and the collector in such a way that the electrons from the emitter could be focused on the collector. The line between the contacts was parallel to C_2.

The effect of an electric field on the probability of specular reflection of electrons was observed on the samples whose surfaces was initially etched by Ar^+ ions. Ion etching of the surface by Ar^+ ions was carried out in a VUP-4 setup; its working

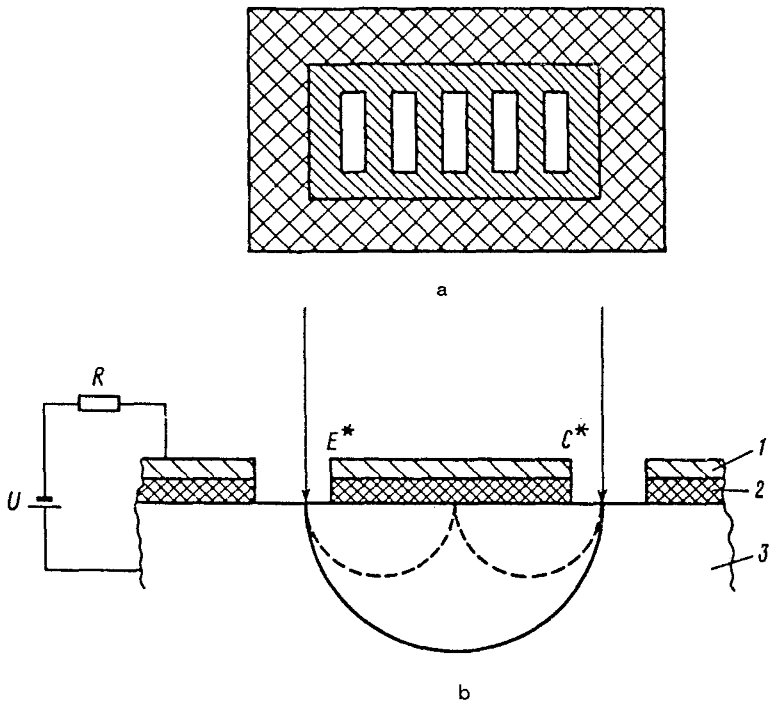

FIG. 1. Experimental setup for observing the effect of an external electric field on the reflection of conduction electrons from the surface of a sample. The vaporized aluminum film is represented by single hatching, and the insulator film, is denoted by double hatching. For clarity, the two parts of the figure (a and b) are drawn to different scales; a) top view of the surface of the sample, b) cross section of the capacitor: *E**—emitter, *C**—collector, *1*—aluminum film, *2*—insulator film, *3*—sample, *U*—voltage source, *R*—ballast resistance. Two electron trajectories are shown, one forming the EF line without reflection from the surface (solid line) and the other, after single reflection from the surface (dashed line).

parameters: an accelerating voltage $\simeq 600$ eV, argon pressure in the chamber $\simeq 10^{-3}$ Torr, etching time $\simeq 1$ min. Ion etching of the surface destroys the atomic order and creates defects on the atomic scale, which radically decrease the probability of specular reflection for the electrons.[5,6]

To create an external electric field normal to the surface of the sample, we built a capacitor (Fig. 1a, b), one face of which was the sample itself, and the other, an aluminum film vaporized on a strip of insulator. A thin film of insulator *2* was deposited on the surface of the sample *3*. Using a photolithographic technique, a number of rectangular openings of dimensions 100×1000 μm were then cut into the insulator, after which a thin film of aluminum *1* was vaporized through a mask covering the openings. In spite of the mask, an electrical contact was created between the film and the sample. To break this contact, a constant voltage of ~ 10 V was applied to the film relative to the sample, causing a large current to pass through the points of electrical contact between the film and the sample. As a result, the aluminum

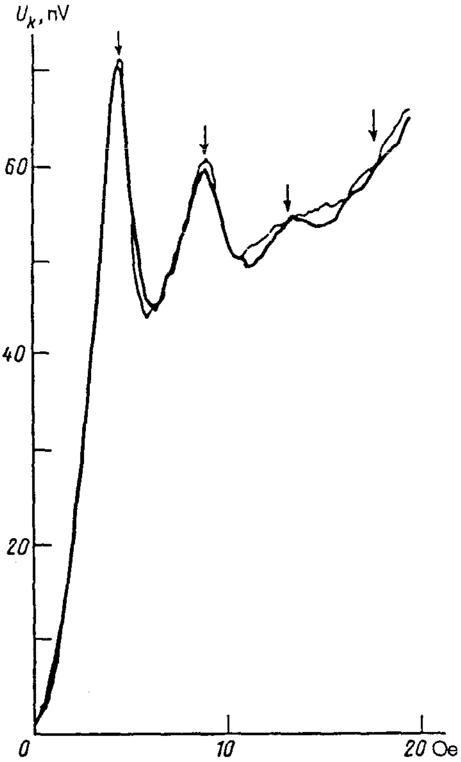

FIG. 2. $U_k(H)$ curves, measured at zero voltage on the capacitor (thin line) and at a voltage of -30 V (thick line).

film at the border of the openings in the insulator "burned up," causing the electric contact between the film and the sample to disappear. A potential contact was attached to the aluminum film by a conductive cement, and the stability of the contact was monitored by measuring the film-sample capacitance. The characteristic value of this capacitance was ~200 pF. As the insulator we used silicon oxide SiO or FP-383 photoresist. SiO was deposited on the sample surface by thermal vaporization in vacuum. The characteristic thickness of the film was ~5000 Å. The photoresist was deposited by means of a centrifuge and its thickness was $\simeq 1$ μm. The thickness of the insulator was determined from the value of the capacitance and with the help of an MII-7 interference microscope.

The contacts, i.e., the collector and the emitter, were mounted on the sample at neighboring openings in the insulator (Fig. 1b). In the experiment we measured the dependence $U_k(H)$ both with and without an electric field present. The intensity of the electric field was near the breakdown value for the given insulator. Using SiO as the insulator, no variations in $U_k(H)$ upon application of the electric field were observed. After vaporization of the SiO film, the probability of specular reflection of the electrons was increased by 0.1–0.15 in comparison with the control part of the sample surface. Using FP-383 photoresist as the insulator, it was possible to observe marked variations in $U_k(H)$ when the external electric field was applied. Figure 2 shows experimental dependences of $U_k(H)$: the thin line is for zero voltage on the capacitor,

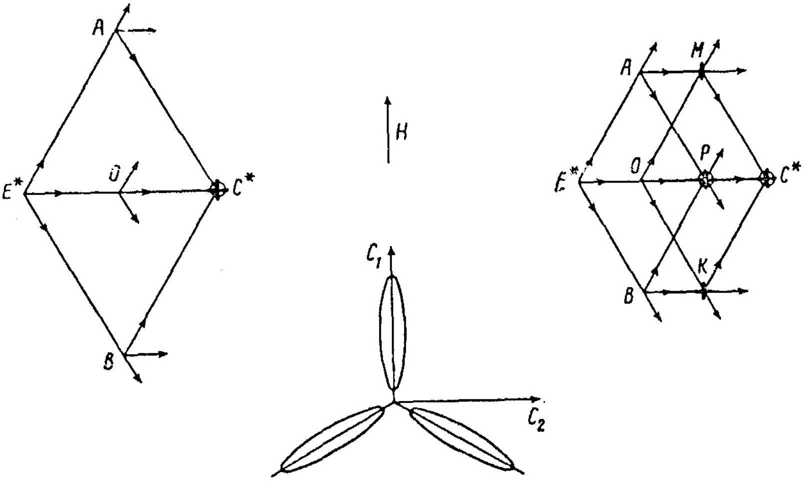

FIG. 3. Projections onto the plane of the sample of the electron valleys (ellipsoids) of bismuth and the electron trajectories forming the second (left) and third EF line (right). C_1 and C_2 are the crystallographic axes, **H** is the magnetic field, E^* is the emitter, and C^* is the collector.

the thick line is for a voltage of 30 V, which corresponds to an electric field on the surface of $\sim 6\times 10^5$ V/cm. Changing the polarity of the applied voltage did not change the shape of the $U_k(H)$ curve. The most important change in $U_k(H)$ is the appearance of a third EF line after application of the voltage, in the absence of which this line is not resolved. At the same time, application of the voltage has virtually no effect on the amplitude of the second line.

The electronic part of the Fermi surface of bismuth consists of three highly elongated ellipsoids, any one of which can be translated into the other by rotating about C_3 by 120° (Fig. 3). The shape of the surface of the ellipsoids is nearly cylindrical. As a result, nearly all the electrons from the emitter move in planes perpendicular to the longer semiaxes of the ellipsoids. For $\mathbf{H}\|C_1$ the Larmor radius of the electrons moving along or parallel to E^*C^* is two times smaller than the Larmor radius of the electrons moving at an angle of 60° with respect to this direction (Fig. 3). The projections of the electron trajectories onto the plane of the sample in Fig. 3 are shown by straight lines. At the points A, O, B, M, P, K, C* the electrons are focused and they are reflected from the surface. The possible directions of motion after reflection are indicated by arrows. For intervalley scattering on the surface the electron changes its plane of motion. The electrons of all three valleys can therefore reach the collector[7] and the amplitude of the EF line in the implemented experimental geometry is determined by the intervalley and the intravalley scattering. The circles and crosses denote the points at which the electron arrives after inter- and intravalley reflection, respectively. At the points without these symbols the electrons are focused without any reflections from the surface. The amplitude of the EF line is determined by the sum of the different possible trajectories the electron can trace from the emitter to the collector, e.g., along E* AMC*, with allowance for the type of surface scattering. The intervalley scattering in the geometry considered here was studied in Refs. 4 and 8. For a single-valley electronic spectrum, the change in the probability Δq results in a change in the amplitude of the nth line. $\Delta A_n \simeq A_1(n-1)q^{n-2}\Delta q$. Note that the change in the amplitude A_n is smaller for larger n since $q<1$. For a multivalley spectrum $A_2=A_1q_e+A_1 2\beta q_{eM}$ and $A_3=A_1q_e^2+A_1 6\beta^2 q^2{}_{eM}$, where β is a coefficient determined by the geometry of the experiment (including the dimensions of the contacts), the structure of the Fermi surface, the nature of the intervalley scattering—random or correlated, and q_{eM} is the probability of intervalley electron-electron scattering. Because of its low probability of occurrence, intervalley electron-hole scattering[9] is ignored. Since $q_e+2q_{eM}=1$ ($\Delta q_e=-2\Delta q_{eM}$), an increase in q_e entails an increase in q_{eM}, and vice versa. For small Δq and equally probable scattering into all of the electron valleys, $\Delta A_2=A_1\Delta q_e(1-\beta)$ and $\Delta A_3=A_1\cdot 2q_e\Delta q_e(1-3\beta^2)$. Recall that EF in multiple fields should be also observed for diffuse reflection[7] since the probability density of an electron falling into a specular state is nonzero. In bismuth, for initially completely diffuse reflection and initially equal probability of reflection into all the electron valleys, $\beta=1$ and there should be no variation in A_2 even for complete suppression of intervalley scattering. This can be explained in the following way (see Fig. 3). In the formation of the second EF line (the left side of Fig. 3) the electrons leaving the emitter and moving in the direction of the collector are initially focused at the point 0. This beam, as a consequence of intervalley scattering, then divides into three different subbeams which moves along the directions indicated in the figure by arrows, and only 1/3 of the electrons focused at the point 0 contribute to the amplitude of the second line. However, each of the two other valleys, whose electrons after leaving the emitter are focused respectively at the points A and B and after intervalley scattering are focused at the collector, contributes 1/3 of the flux. If intervalley scattering is eliminated, the EF line will be formed only by electrons of one valley and the entire stream after reflection at the point 0 will arrive at the collector and contribute to the amplitude of the line. Thus, if intervalley scattering is excluded, no variations will take place in the stream forming the second EF line. Analogous considerations show that at the same time a change in the amplitude of the third line (see the right side of Fig. 3) should take place and it should be of the opposite sign to the case of a single-valley electron spectrum.

Earlier studies of the reflection of electrons from a bismuth surface have shown[4] that completely diffuse reflection takes place in the case of an ion-etched surface. Preliminary investigations showed that the surface of the samples was originally charged. The magnitude of the charge is so large that is accounts for the difference in the character of the reflection of the electrons and the holes. The manifestation of the field effect under these conditions was considered above and should express itself in the following: 1) the effect depends on the polarity of the field; 2) the field does not affect the amplitude of the second EF line; 3) the decrease in the probability of intravalley reflection caused by the field effect leads to an increase of the amplitude of the third EF line and vice versa. Such behavior has been observed experimentally. The low probability of specular reflection does not permit one to observe any variations in the amplitudes of lines with higher numbers. In the case of nonequivalence of the valleys due to either some difference between them or, possibly, the orientation of the surface normal to the crystallographic axes of the sample, the magnitude and sign of the field effect are determined by the value of β.

The change in the probability of specular reflection upon application of an electric field was estimated from the experimental data obtained in this study. We obtained the value $\Delta q_e \simeq -2\Delta q_{eM} \sim 0.1$.

[1] V. Ya. Kravchenko and É. I. Rashba, Zh. Eksp. Teor. Fiz. **56**, 1713 (1969) [Sov. Phys. JETP **29**, 918 (1969)].
[2] V. S. Tsoĭ and I. I. Razgonov, Pis'ma Zh. Eksp. Teor. Fiz. **23**, 107 (1976) [JETP Lett. **23**, 92 (1976)].
[3] V. S. Tsoĭ, Pis'ma Zh. Eksp. Teor. Fiz. **19**, 114 (1974) [JETP Lett. **19**, 70 (1974)].
[4] S. I. Bozhko, I. F. Sveklo, and V. S. Tsoĭ, Fiz. Nizk. Temp. **15**, 710 (1989) [Sov. Phys. Low Temp. Phys. **15**, 397 (1989)].
[5] S. I. Bozhko, V. S. Tsoĭ, and S. E. Yakovlev, Pis'ma Zh. Eksp. Teor. Fiz. **36**, 123 (1982) [JETP Lett. **36**, 153 (1982)].
[6] S. I. Bozhko and V. S. Tsoĭ, Fiz. Nizk. Temp. **13**, 1139 (1987) [Sov. Phys. Low Temp. Phys. **13**, 1139 (1987)].
[7] V. S. Tsoĭ and Yu. A. Kolesnichenko, Zh. Eksp. Teor. Fiz. **78**, 2041 (1980) [Sov. Phys. JETP **51**, 1027 (1980)].
[8] V. V. Andrievskiĭ, E. I. Ass, and Yu. F. Komnik, Fiz. Nizk. Temp. **11**, 1148 (1985) [Sov. Phys. Low Temp. Phys. **11**, 631 (1985)].
[9] I. F. Sveklo and V. S. Tsoĭ, Pis'ma Zh. Eksp. Teor. Fiz. **49**, 290 (1989) [JETP Lett. **49**, 331 (1989)].

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