Screening of irregularities on a bismuth surface by the electron pair potential

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Screening of the roughness of a surface by the electron pair potential has been observed through focusing of conduction electrons. The fraction of the surface area which constitutes an *n–s* boundary is determined.

Transverse electron focusing[1] is an effective method for studying Andreev reflection.[2–5] The amplitude of the electron-focusing lines was measured in Refs. 2–5 for the case of intravalley electron scattering. A study of intervalley electron scattering at a surface[6] during Andreev reflection opens up some additional methodological possibilities for studying electron reflection: observing the screening of surface roughness by the electron pair potential, determining the fraction of the area of the surface which constitutes an *n–s* boundary, determining the position of the "reflecting plane" during the formation of a boundary in a heterojunction, and observing electron pairing from different valleys.

We know that as the angle of incidence of a light beam on a reflecting surface is reduced the diffuse component of the reflection is suppressed. In conductors, as current carriers are reflected from the surface of a sample, the screening of the roughness by the field of the surface charge (near-surface band curvature) may prove to be more effective in producing a similar effect.[7] Since the length of the electron wave and the screening radius are quantities of the same order of magnitude, during normal incidence on a surface and during intravalley scattering the change in the probability for specular reflection due to the screening of roughness is small. It was shown in Ref. 8 that in bismuth the predominant mechanism for the suppression of intravalley specular reflection is intervalley scattering.

The effectiveness of intervalley scattering in bismuth is determined by the roughness of atomic scale. Since the screening radius in bismuth is ~ 600 Å, the screening of a roughness of atomic scale prevents intervalley scattering and thereby significantly increases the probability for intravalley specular reflection. It is preferable to directly measure the probability for intervalley scattering itself and the influence on this process of the screening of the roughness due to band bending. By analogy with the screening of surface roughness by a surface-charge field when an *n–s* boundary is formed, surface irregularities are screened by the electron pair potential. In this case the screening length is on the order of the coherence length $\xi \gg a$, where a is the interatomic distance.

A study of intervalley scattering can thus be utilized to detect screening of irregularities in a reflecting surface.

There is a realistic possibility of observing the screening of a surface roughness by an electron pair potential at a bismuth-tin interface. There are several pieces of indirect evidence for the existence of a proximity effect in this system. First, there is a proximity effect in bismuth-lead film structures[9] (the coherence length in bismuth is[9] ~ 300 Å). Second, the radical differences in the structure of the electronic spectra of these metals should apparently give rise to significant reflection of current carriers from a bismuth-tin interface. This conclusion is consistent with, in particular, the fact that the diffuse nature of the reflection of electrons from the surface of a sample is not altered by the deposition of a tin film on bismuth. On the other hand, the maximum observed probability for Andreev reflection at a bismuth-tin interface is unity.[5] This result is indirect evidence for a proximity effect in the bismuth-tin system.

In the measurements of the electron focusing we used bismuth samples whose surfaces were oriented perpendicular to C_3 and covered with a tin film. The film was deposited in ultrahigh vacuum by the technique described in Ref. 4. Figure 1 shows Auger spectra recorded before the sample surface was cleaned by ion bombardment (curve 1), after the surface was cleaned by bombardment with 150-eV Ar^+ ions for 1 h (curve 2), after the sample was heated at 420 K

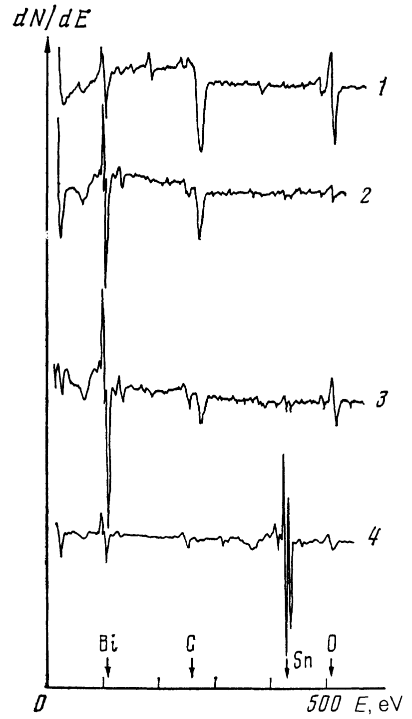

FIG. 1. Auger spectra of the surface of a bismuth sample. 1—Before the surface is cleaned by ion bombardment; 2—after the surface is cleaned by bombardment for 1 h by 150-eV Ar^+ ions; 3—after the sample is heated at 420 K for 1 h; 4—after the deposition of the tin film. The sensitivity of the measurement apparatus was reduced by a factor of 2.5 for the recording of curve 4. The positions of characteristic Auger peaks along the energy scale are shown for bismuth, carbon, tin, and oxygen.

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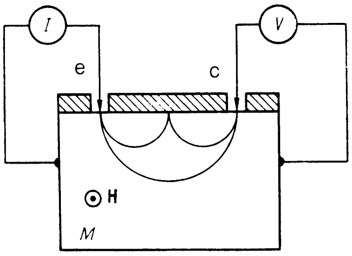

FIG. 2. M—Sample; I—current source; V—voltmeter; hatching—tin film. The paths traced out by the quasiparticles which form the electron-focusing line are shown for $H = H_1$ and $H = 2H_1$.

for 1 h (to relax the structural defects at the surface after the ion bombardment; curve 3), and after the deposition of the tin film (curve 4). The thickness of the deposited film was determined after the sample was extracted from the ultra-high-vacuum chamber. The thickness was measured with an MII-4 interference microscope and was found to be ~ 500 Å. Interestingly, the height of the bismuth Auger peak decreases by a factor of only two despite the large thickness of the deposited film. The most likely explanation for this result is that the deposited film has an island character, although there is the further possibility of diffusion of bismuth atoms through the tin film to the surface.

The experimental layout is shown in Fig. 2. Two point contacts were fabricated on the surface of the sample: an emitter e and a collector c. An alternating electric current was passed through the emitter, and the collector voltage U_c was measured as a function of the strength of the magnetic field, H. The field **H** lay in the plane of the sample and was in most cases perpendicular to the line connecting the emitter-collector contacts, **L**. Some of the measurements were taken with **H** deflected away from the normal to **L**; in such cases, the particular deviation of **H** from the normal to **L** is specifically stated in the description of the experimental geometry.

For a study of the intravalley electron scattering, the line of contacts **L** was oriented along C_2, and the magnetic field was in the orientation **H**⊥**L** (Refs. 1–5). In this experimental geometry (Fig. 3, a and b) the first electron-focusing line is formed by electrons of the central cross section of one of the ellipsoids (1) of the Fermi surface of bismuth. Two groups of electrons contribute to the amplitude of the second electron-focusing line: electrons of ellipsoid 1 which have undergone specular reflection from the surface at point Γ and electrons of ellipsoids 2 and 3 which have undergone intervalley scattering into valleys 3 and 2 at points E' and E. The lengths of paths eEc and eE'c are twice that of path eΓc, so the relative contribution of the electrons of the second group to the second electron-focusing line depends on the distance between the contacts and on the electron mean free path. When the direction of the magnetic field **H** deviates from the normal to **L**, the hop lengths of electrons belonging to ellipsoids 2 and 3 of the Fermi surface become equal, and the electrons of the second group cease to reach the collector.

It follows from the geometric model of electron focusing[10] that the amplitude of the first electron-focusing line for a cylindrical Fermi surface is $\sim (d/L)^{1/2}$, where d is the size of the contact. It also follows that the relative width of the first electron-focusing line is $\Delta H_1/H_1 \sim d/L$, where ΔH_1 is the width of the first electron-focusing line measured at the half-height level, and H_1 is the field in which the first electron-focusing line is observed. For the second electron-focusing line, $\Delta H_2/H_2$ depends on the nature of the reflection of electrons from the surface. For specular reflection we would have $\Delta H_2/H_2 = \Delta H_1/H_1$, while for completely diffuse reflection we would have $\Delta H_2/H_2 = 2\Delta H_1/H_1$. Diffuse reflection of electrons at point Γ (Fig. 3b) is equivalent to a shift of the emitter from e to Γ or, equivalently, a halving of L.

For $T > T_C$ we observed an electron focusing of electrons of the central cross section of ellipsoid 1; the ratio of the amplitude of the second electron-focusing line to that of the first was $A_2/A_1 = 0.24$ The relative widths of the first and second lines were the same; this agreement is evidence of specular intravalley electron scattering. The reason for the decrease in the amplitude of the second line is that some of the electrons undergo intervalley scattering. When the direction of the magnetic field deviates from the normal to the line of contacts, the amplitude of the second electron-focusing line decreases: $\Delta A_2/A_1 = 0.08$, where ΔA_2 is the change in the amplitude of the second line when **H** deviates from the normal to **L**. It follows that as they are reflected from the surface the electrons become distributed in an essentially equiprobable fashion among all three electron valleys of the Fermi surface.[8]

As the temperature T is lowered below T_C, the amplitude of the second electron-focusing line increases and changes sign (Fig. 4). The electrons which had previously undergone specular intravalley scattering at point Γ begin to experience Andreev reflection.[2–5] The amplitude of the second electron-focusing line is independent (to within 3%) of the angle made by the magnetic field with the normal to **L** over the range $\pm 40°$. This independence is evidence of a significant decrease in the intervalley scattering. This study of intravalley scattering of electrons by an n–s interface at $T < T_C$ has made it qualitatively clear that the probability

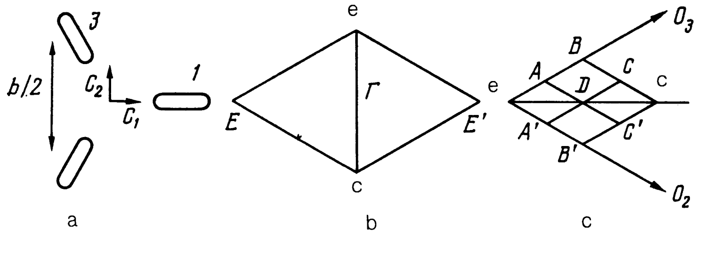

FIG. 3. a: Projection of electron ellipsoids 1–3 of the Fermi surface of bismuth onto a trigonal plane. This figure is not drawn to scale. **b**—Reciprocal-lattice vector of the surface. b: Projections of the paths traced out by electrons of ellipsoids 1, 2, and 3 onto the surface of the sample in a magnetic field (**L**‖C_2,**H**⊥**L**). c: Projections of the paths traced out by electrons of ellipsoids 2 and 3 onto the surface of the sample in a magnetic field (**L**‖C_1,**H**⊥**L**).

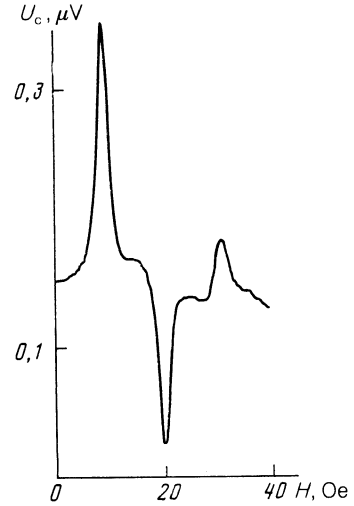

FIG. 4. $U_c(H)$ at $T = 1.7$ K with $\mathbf{L} \| C_2$ and $\mathbf{H} \perp \mathbf{L}$.

for intervalley scattering falls off substantially as T falls below T_C.

To obtain a quantitative measure of the change in the probability for intervalley electron scattering, it is preferable to carry out the measurements in the following experimental geometry: With the line of contacts **L** oriented along C_1 (Fig. 3c), with $\mathbf{L} \perp \mathbf{H}$, the electron-focusing lines are formed only by the electrons which have undergone intervalley scattering.[6] In the case of intravalley scattering, the electrons of ellipsoids 2 and 3 which have been emitted from emitter e move along the lines eO_2 and eO_3, respectively, and do reach the collector. The electron-focusing line due to the electrons of the central cross section of ellipsoid 1 is not seen because of the long path of these electrons. The first electron-focusing line is formed by the electrons of ellipsoid 2 (3) which have undergone intervalley scattering at point B′ (B) to ellipsoid 3 (2). Three groups of electrons, reflected in different ways by the surface of the sample, contribute to the amplitude of the second electron-focusing line. Figure 3c shows

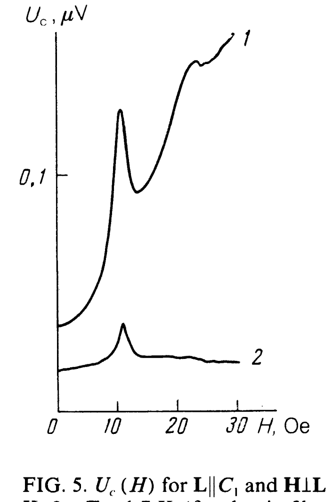

FIG. 5. $U_c(H)$ for $\mathbf{L} \| C_1$ and $\mathbf{H} \perp \mathbf{L}$ for various temperatures: 1—$T = 4.2$ K; 2—$T = 1.7$ K (for the tin film, $T_C = 3.7$ K). The curves have been shifted arbitrary distances along the ordinate axis.

projections onto the surface of the sample of the paths of the electrons which form the second electron-focusing line: 1) $\mathrm{eA'\overline{B}\,'C'c}$, $\mathrm{eA\overline{B}\,Cc}$; 2) $\mathrm{e\overline{A}\,D\overline{C}\,'c}$, $\mathrm{e\overline{A}\,'D\overline{C}c}$; 3) $\mathrm{e\overline{A}\,\overline{D}\,Cc}$, $\mathrm{e\overline{A}\,'\overline{D}\,\overline{C}\,'c}$ (the letters are the points at which the electrons collide with the surface; the points represented by letters with a superior bar are intervalley scattering points). We thus find the following results for the amplitudes of the first and second electron-focusing lines:

$$\tilde{A}_1 = 2A_1 W_v, \quad \tilde{A}_2 = 2A_1 (W_i^2 W_v + W_i W_v^2 + W_v^3),$$

where W_i and W_v correspond to the electron intravalley and intervalley scattering efficiencies, A_1 is the amplitude of the line in the focusing of electrons without reflections from the surface (**L** along C_2), and $\tilde{A}_1$ and $\tilde{A}_2$ are the amplitudes of the first and second lines (**L** along C_1).

The results of measurements of the electron focusing at two temperatures are shown in Fig. 5. The following features are noteworthy.

1. An electron-focusing line exists after T is brought below T_C.

2. When T is brought below T_C the polarity of the electron-focusing line does not change, despite the fact that the line is formed by electrons reflected from the surface.

3. As T_C is crossed, the amplitude of the first electron-focusing line falls off significantly (by a factor ~ 4), while during intravalley scattering there is essentially no change in A_1 as T is brought below T_C (Refs. 2 and 5). As T is brought below T_C, in both intravalley and intervalley scattering, the monotonic $U_c(H)$ behavior characteristically undergoes a marked weakening.

The observation of electron-focusing lines at $T < T_C$ means that intervalley scattering is occurring. The fact that the excitations which shape the line do not change polarity is evidence that the reflection occurs without a change in the type of excitation. Since the change in Δ at the n–s interface occurs over distances $\sim \xi$, the scale of the roughness of the n–s interface is much larger than a, and the roughness is ineffective for intervalley scattering. Consequently, not all of the reflecting surface constitutes an n–s interface. A decrease in the area of the n–s interface may occur because the tin film is an island film[4] and/or because there is an insulating layer at the bismuth-tin interface. Note that the small Fermi energy for electrons in bismuth, $\varepsilon_F = 0.028$ eV, causes an insulating layer with a thickness of only ~ 1 monolayer to have a low transparency, $\sim 10^{-2}$. We thus see the need for stringent requirements in terms of the cleanliness of the n–s interface.

Taking into account the decrease in the area of the n–s interface and the fact that Andreev reflection occurs during intravalley scattering, we find the amplitudes of the first and second electron-focusing lines at $T < T_C$:

$$\tilde{A}_1 = 2A_1 W_v \gamma,$$

$$\tilde{A}_2 = 2A_1 (\gamma W_v W_i^2 (2\gamma - 1)^2 + \gamma^2 W_v^2 W_i (2\gamma - 1) + \gamma^3 W_v^3),$$

where γ is the fraction of the surface area which is free of the n–s interface. From the ratio of the amplitudes of the first electron-focusing lines at $T < T_C$ and $T > T_C$ we can determine γ. In the case at hand we find $\gamma = 0.25$. For this value of γ, we calculate $\tilde{A}_2/\tilde{A}_1|_{T < T_C} = 0.01$. This result explains the disappearance of the second electron-focusing line at $T < T_C$.

The weakening of the monotonic tendency in the $U_c(H)$ dependence apparently occurs because under Andreev-reflection conditions the quasiparticles which reach the collector can have both positive and negative charges. A calculation based on the geometric model for electron focusing with intravalley scattering explains this behavior.[5]

In summary, a study of intervalley scattering during Andreev reflection makes it possible to observe screening of surface irregularities by the electron pair potential and to determine the relative area of the surface which constitutes an n–s interface.

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