Energy dependence of the probability for Andreev reflection

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An experiment has been carried out to directly observe the dependence of the Andreev reflection probability q_A on the excitation energy ϵ in the case of normal incidence on an *n-s* interface by means of transverse electron focusing {V. S. Tsoĭ, Pis'ma Zh. Eksp. Teor. Fiz. **19**, 114 (1974) [JETP Lett. **19**, 70 (1974)]}.

One application of a point contact between two metals under conditions such that the size of the contact is much smaller than the electron mean free path l (a Sharvin probe) is as an injector (emitter) of nonequilibrium current carriers.[2] The simplicity with which the apparatus can be assembled and with which the extent of the deviation from equilibrium can be varied, over a wide energy range, opens up some further opportunities for studying the kinetics of nonequilibrium electrons. Experiments have been carried out in this direction in an arrangement with longitudinal electron focusing[3] and also in an arrangement with transverse electron focusing.[4,5] In the present experiments we used electron focusing to study the dependence of q_A on ϵ. The energy dependence of the Andreev reflection was studied in Refs. 6–8.

To fabricate the *n-s* interface, we used the procedure of Ref. 9, with one modification: To clean the surface of the bismuth sample before the deposition of the tin film, we used an ion beam with a lower energy, 150 eV, for an etching time of 1.5 h. After the sample was annealed at 180 °C for 4 h, we observed low-energy electron diffraction by the surface of the sample. In these measurements the C_3 crystallographic axis was oriented perpendicular to the surface of the sample. The intensity of the diffraction pattern, the energy profiles of the intensity, and the relation between the amplitudes of the reflections and the background were approximately the same as those observed in low-energy electron diffraction by the antimony (111) surface.[10] The surface of a

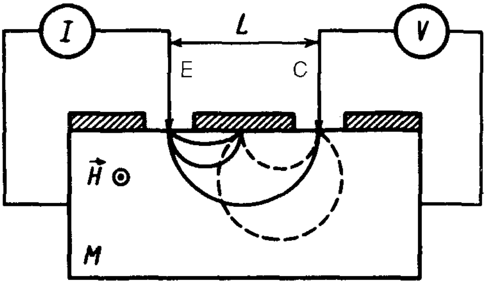

FIG. 1. *M*—The sample; *I*—the current source; *V*—a voltmeter. The hatching shows the tin film. The trajectories of effective quasiparticles are shown (by solid lines for electron quasiparticles and by dashed lines for hole quasiparticles) for three values of *H*: $0<H<2H_0$, $H=H_0$, $H=2H_0$.

sample contained a small level of oxygen and carbon impurities. A tin film with a thickness of 640 ± 70 Å was then deposited on the surface of the sample. Despite the significant thickness of this film, the height of the Auger peak of bismuth (at the energy 103 eV) decreased only 30% from the height before the film deposition. This result is evidence that the film is of an island nature; it may also indicate a segregation of the bismuth. Furthermore, we observed the low-energy electron diffraction on the surface of the sample from a bismuth substrate on which a (6×6) reconstruction had occurred. The sample was then taken out of the ultrahigh-vacuum chamber, and further manipulations of the sample were carried out under ordinary conditions. Regions lacking a superconducting film were produced around the point contact by placing it on the sample at a voltage ~100 V. In some cases this procedure had to be repeated several times.

The experimental arrangement is shown in Fig. 1. The contacts, the emitter *E* and the collector *C*, are placed along the C_2 axis. The magnetic field **H** lies in the plane of the sample and is perpendicular to C_2. A current $I_E^{\sim} = I_0 \sin \omega t$, is passed through *E*, and the amplitude of the alternating voltage at *C*, $U_C^{\sim}$, is measured. In this particular experimental geometry the second electron-focusing line is formed by electrons which have been reflected once in the region of the part of the surface of the sample covered with the tin film. The nature of the reflection was studied as a function of the excitation energy by a modulation method[4]: We measured the dependence of the amplitude of the electron-focusing line on the magnitude of the direct current, $I_E^{=}$ $(I_E = I_E^{=} + I_0 \sin \omega t;\ I_0 = \text{const} \ll I_E^{=})$. The accelerating voltage was $U_E^{=} = I_E^{=} R_E$. In the experiments, the resistance of the emitter, R_E, was about 1 Ω, and the current I_0 was 2×10^{-5} A. For observation of the focusing of excitations with an energy ϵ, it is important that $l(\epsilon)$ be greater than or at the least on the order of the distance between contacts, L. In our experiments, L did not exceed 100 μm, with a minimum value of 40 μm.

Figure 2 shows experimental traces of $U_C^{\sim}(H)$ for various values of $U_E^{=}$ at $T = 1.6$ K. The critical temperature of the tin film is $T_c = 3.4$ K (it was determined from the sharp decrease in the monotonic behavior of $U_C^{\sim}$ as a function of H). The polarity of the static voltage was chosen such that electrons near the emitter were accelerated; a negative emitter generated electron excitations. In a field H_0 we observe an electron-focusing line which results from the focusing of excitations which have left the emitter and which have reached the collector without reflections from the surface.

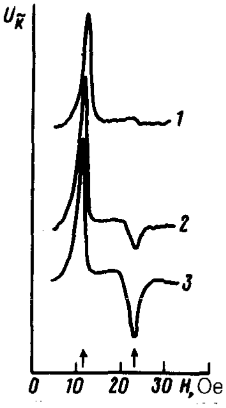

FIG. 2. The dependence $U_C^{\sim}(H)$ for various values of $U_E^{=}$ ($L = 82$ μm, $R_E = 0.78\ \Omega$). Curves 1–3 were recorded at respective $U_E^{=}$ values of 3.9, 0.7, and 0 mV. The values of H_0 and $2H_0$ are marked on the abscissa scale. The curves have been displaced an arbitrary distance along the ordinate.

In a field $2H_0$ we observe a peak in the collector voltage of the other polarity, which results from excitations after the Andreev reflection.[9,11] Figure 3 shows the amplitude of the second electron-focusing line divided by the amplitude of the first, $q_A^* = A_2/A_1$ as a function of[9,11] $U_E^{=}$ ($q_A^* \sim q_A$). In the simplest case, the only difference between the superconducting and normal phases is that the size of the superconducting gap is zero in the normal phase, and at the transition to the superconducting phase this gap abruptly changes to a magnitude Δ (in our case, $\Delta = 0.50$ meV) and is a constant. In this case the ϵ dependence of q_A is $q_A = 1$ at $\epsilon \leqslant \Delta$ and $q_A\{(\epsilon/\Delta) - [(\epsilon/\Delta)^2 - 1]^{1/2}\}^2$ at[12] $\epsilon > \Delta$. If we assume that the distribution function of the excitations is $f(\epsilon; eU_E^{=}) = f_0(\epsilon - eU_E^{=})$, where f_0 is a Fermi distribution for the temperature T, we find that the relative number of the particles which have experienced an Andreev reflection and which have been detected by the modulation technique is $N(U_E^{=}) = \int_{-\infty}^{+\infty}(-\partial f/\partial\epsilon) q_A(\epsilon) d\epsilon \times [\int_{-\infty}^{+\infty}(-\partial f/\partial\epsilon) d\epsilon]^{-1}$. The solid line in Fig. 3 shows the functional dependence $N(U_E^{=})$. For simplicity, we have assumed $q_A = 0$ at $\epsilon > \Delta$. The ordinate scale has been chosen such that at $U_E^{=} = 0$ the value of N agrees with q_A^*. We see that $N(U_E^{=})$ gives a satisfactory description of the dependence of q_A^* on $U_E^{=}$ at $U_E^{=} \lesssim \Delta$. The agreement can be improved by allowing for the circumstance that the effective

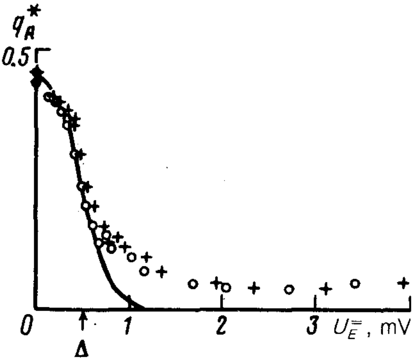

FIG. 3. The arrow on the abscissa scale shows the value of Δ.

accelerating voltage could be only a fraction $U_E^= - U_{\text{eff}}^= = pU_E^=$. The open circles in Fig. 3 correspond to the value $p = 0.87$. The existence of a negative electron-focusing line at $U_E^= \gg \Delta$ is interesting (curve 1 in Fig. 2; also Fig. 3). The apparent reason for this result is that at large values of $U_E^=$ relaxation processes in the vicinity of the emitter lead to a synchronous generation of excitations with $\epsilon < \Delta$.

In summary, it has been demonstrated experimentally that electron focusing can be used to study the ϵ dependence of q_A for a local group of electrons. This possibility opens up some extensive methodological opportunities for studying this dependence. Specifically, it becomes possible (1) to determine the role played by the excitation on the Fermi surface (to determine the role played by the angle of incidence in the case of a spherical Fermi surface) and (2) to study surface states near an *n-s* interface.[13]

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