Observation of Andreev reflection with the help of transverse electron focusing

S. I. Bozhko, V. S. Tsoĭ, and S. E. Yakovlev
Institute of Solid State Physics, Academy of Sciences of the USSR

(Submitted 2 July 1982)
Pis'ma Zh. Eksp. Teor. Fiz. **36**, No. 4, 123–126 (20 August 1982)

Experimental results on the direct observation of Andreev reflection with the help of transverse electron focusing (EF) are presented (Ref. 1).

PACS numbers: 41.80.Dd

As shown by Andreev,[2] when a quasiparticle, incident from a normal phase (n) on a boundary with a superconducting phase (s), is reflected, the signs of the velocity vector, charge, and effective mass of the quasiparticle change (Andreev reflection).

Until now, extensive experimental information has been accumulated on indirect observation of Andreev reflection in studying the kinetic properties of superconductors. Krylov and Sharvin[3] observed Andreev reflection directly with the help of the radio-frequency size effect. The use of EF for studying the reflection of electrons from an *n–s* boundary is obvious.[4] In this work, EF is used to observe Andreev reflection directly.

In order to create an *n–s* boundary, we used the following procedure. We placed a single-crystal bismuth plate into an ultrahigh vacuum chamber, that was evacuated to a pressure $\sim 10^{-9}$ Torr. The normal to the surface of the plate **n** coincided with the C_3 axis. With a sublimation pump operating in the chamber, we injected especially pure argon up to a pressure $\sim 10^{-4}$ Torr. We cleaned the surface of the specimen under these conditions by bombarding with a normally incident beam of argon ions with energy ≈ 300 eV for 1 hour. After this procedure, the specimen was moved to the analysis chamber, where it was annealed in a vacuum of $\sim 10^{-10}$ Torr for 4 hours at a temperature of ≈ 200 °C. After this treatment, the content of impurities on the surface of the specimen did not exceed 1/100 monolayers, which was monitored with the help of an Auger spectrometer. Then we sputtered a tin film with a thickness of ~ 1 μm on the surface of the specimen. After this the specimen was removed from the ultrahigh vacuum apparatus and further manipulation of the specimen was performed under normal conditions. Using a photolithographic technique, we left a system of tin strips with width ≈ 0.15 mm parallel to the C_1 axis on the surface of the specimen.

A diagram of the experiment is presented in Fig. 1. We positioned the emitter (E) and collector (C) contacts on different sides of one of the strips so that the line of contacts was perpendicular to C_1. In the geometry used for the experiment, the first EF line is formed by nonequilibrium electrons leaving the emitter and reaching the collector without reflection from the surface. The second EF line is formed by electrons, which are reflected once in the region of the specimen surface covered by the tin film. In a preliminary series of experiments, we determined the reflecting properties of the surface at different stages of the working process described above. Before ionic bombardment of the surface, the probability for specular reflection of electrons with normal incidence q is high ≈ 0.8. Ionic bombardment considerably suppressed the specular nature of the reflection: q decreased to 0.1–0.2. The deposition of the tin film had virtually no effect on the dependence of the collector voltage U on the magnetic field **H** with the specimen temperature T greater than the critical temperature of the

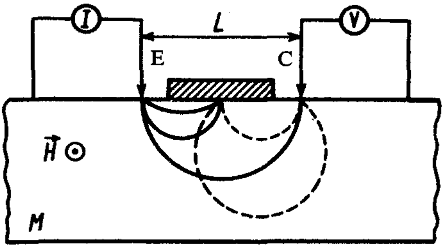

FIG. 1. M) Specimens; I) current source; V) voltmeter; E) emitter; C) collector. The shaded area represents the tin film. The figure shows the effective quasiparticle trajectories (the electronic trajectories are represented by the continuous curves and the hole trajectories are denoted by the dashed curves) for three values of H: $0 < H < 2H_0$, $H = H_0$, $H = 2H_0$.

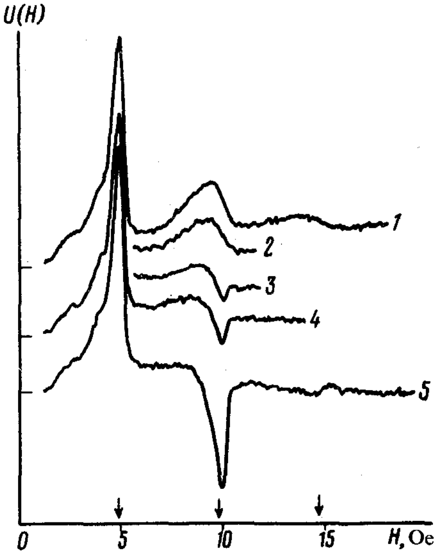

FIG. 2. The curves $U(\mathrm{H})$ at different temperatures. The curves 1–5 are presented for specimen temperatures of 3.80, 3.78, 3.74, 3.70, and 2.78 K, respectively. The arrows of the abscissa axis indicate the quantities H_0, $2H_0$, and $3H_0$. The curves are arbitrarily shifted along the ordinate axis and the values of $U(0)$ are indicated on the axis for $T = 3.80$, $T = 3.70$, and $T = 2.78$ K.

film T_c. Examples of traces of $U(\mathrm{H})$ for different T are presented in Fig. 2. Lowering T below T_c leads to two basic features in the dependence $U(\mathrm{H})$: 1) in a field $2H_0$, there is a negative EF line whose amplitude increases as the temperature decreases (H_0 is the field in which the first EF line is observed and 2) the monotonic behavior decreases.

In terms of excitations, the polarity of the EF line is determined by the sign of the excitations focused on the collector. For reflection without a change in the type of excitation, the sign of the focused excitations is determined by the polarity of the applied voltage, which we shall define as being positive. Since the same Lorentz force $(e/m)[\mathrm{VH}]$ acts on the electron and hole excitations, the EF lines formed by different types of excitations must be observed with the same values of the magnetic field. In the case of Andreev reflection, the type of excitation changes and for the geometry of the experiment used, a negative EF line should be observed in a field $2H_0$,[1)] which was observed experimentally. A theoretical calculation[7] confirms the qualitative considerations presented.

The fraction of Andreev-reflected quasiparticles is determined by the number of quasiparticles $N(\epsilon < \Delta)$ with energy $\epsilon < \Delta$, where ϵ is the energy of the quasiparticle and Δ is the magnitude of the energy gap in the superconductor. If excitations with ϵ such that $0 \leqslant \epsilon \leqslant \epsilon^*$, $\epsilon^* \geqslant \Delta$ reach the n–s boundary, then the amplitude of the negative line is proportional to $N(\epsilon < \Delta) \sim \Delta$. The ratio Q of the amplitude of the negative line to the amplitude of the first EF line must be determined exclusively by the quantity Δ. Figure 3 shows the following temperature dependences 1) $\Delta(T)/\Delta(0)$ according to BCS (continuous curve); 2) $Q(T)$ for several series of measurements (various symbols). For

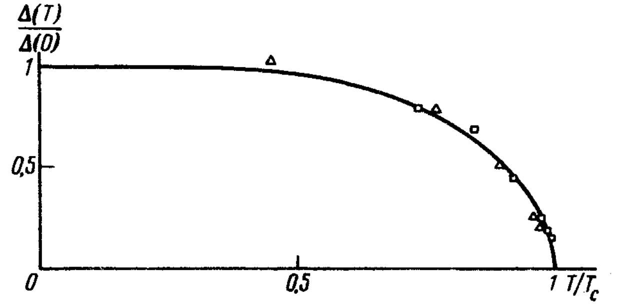

FIG. 3.

the experimental data, the scale along the ordinate axis was chosen so as to obtain the best agreement with the theoretical curve. It is evident from Fig. 3 that the dependence $Q(T)$ is satisfactorily described by the temperature dependence of Δ.

We note that the fraction of Andreev-reflected quasiparticles is not equal to Q. This is due to the fact that with reflection the projection of the quasiparticle velocity along the direction of the magnetic field changes and quasiparticles that previously did not reach the collector due to displacement along the field return to the contact line and can reach the collector. In the case of a spherical Fermi surface, the number of effective electrons with specular reflection is $N_3 \sim (b/L)(b/L)^{1/2}$, where b is the size of the contact and L is the distance between contacts. The first cofactor results from the limitation on the number of electrons due to their drift along the magnetic field and the second is due to the decrease in the length of the jump along the contact line. In the case of Andreev reflection, the number of effective electrons $N_A \sim (b/L)^{1/2}(b/L)^{1/2}$, since for both momentum components $\mathbf{p}_\perp$ and $\mathbf{p}_\parallel$ ($\perp$ and $\parallel H$) on the number of electrons is limited by the decrease in the length of the jump along the contact line. $N_A/N_3 \sim (L/b)^{1/2}$. The quantity N_A/N_3 is determined exclusively by the geometry of the Fermi surface (in bismuth, N_A/N_3 must be less than $(L/b)^{1/2}$).

The role of roughness on the surface changes radically in the presence of Andreev reflection. First, roughness of the n–s boundary cannot be much smaller than the correlation length ξ, i.e., the minimum size of roughness is $-\xi$. Second, deviation of the local normal to the surface from $\mathbf{n}$, which suppresses the specular nature of the reflection with the usual reflection, is not significant with Andreev reflection, since the direction of the local normal does not affect the direction of motion of the reflected quasiparticle, which is determined by the direction of the momentum of the quasiparticle incident on the n–s boundary. The suppression of Andreev reflection with glancing incidence of quasiparticles[8] can be neglected.

As far as the nature of singularities in fields $3H_0$, $4H_0$ and so on is concerned, it is not possible to draw definite conclusions at this stage of the work due to the incomplete determination of the position and width of the n–s boundary.

Thus, the direct observation of Andreev reflection using the EF method has been realized experimentally. This allows us to look forward to using the EF method to study the probability of Andreev reflection as a function of the quasiparticle energy and the angle of incidence on the n–s boundary.

We thank A. F. Andreev, É. I. Rashba, Yu. V. Sharvin, and V. V. Schmidt for useful discussions.

[1)] The displacement of the second line into the low-field region with the usual reflection (upper curve in Fig. 2) could be due to two reasons: 1) inflection of bands near the surface[5]; 2) surface microstructure.[6]

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Translated by M. E. Alferieff
Edited by S. J. Amoretty