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Nonequilibrium carrier transport in superconducting niobium-silicon heterostructures

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Carrier transport through a 50-nm-thick single-crystal silicon film sandwiched between two superconducting electrodes is studied. A strongly voltage-dependent normal current is found, substantially below the value in the normal state, together with the structure at submultiples of the superconducting energy gap. The results are explained as a hot-electron effect, taking into account elastic and Andreev scattering at the interfaces and ignoring energy relaxation in the silicon. It is argued that the elastic scattering at the interfaces is due to Fermi-momentum mismatch.

In recent years, interest in semiconductor-superconductor heterostructures has risen because of their potential as three-terminal superconducting devices.[1-4] Most experimental and theoretical work on this subject has focused on the *zero-voltage* current through superconductor(S)-semiconductor(SM)-superconductor(S) structures, which is understood as a manifestation of the proximity effect in analogy to superconductor–normal-metal–superconductor (S-N-S) structures. Superconducting Cooper pairs diffuse from the superconductor into the semiconductor over a characteristic length that depends on the carrier concentration, effective mass, and elastic scattering. If the semiconductor is thin compared to the decay length, a supercurrent will flow.[5] Very recently, interest has grown in several older theoretical ideas[6,7] in which ballistic transport through the semiconductor is assumed.[8-10] In this case, phase coherence in the semiconductor governs electronic transport and the supercurrent is believed to be carried by the discrete excitation spectrum in the semiconductor, instead of the more phenomenological interpretation based on the proximity effect.

In this Rapid Communication we report on a detailed analysis of current transport at *finite voltages* in a model system consisting of a thin silicon membrane sandwiched between two superconducting electrodes. As will be shown, carriers are scattered elastically while passing through the semiconductor, but inelastic scattering is negligible. As a consequence, an applied voltage induces a strongly energy-dependent nonequilibrium distribution of carriers in the bulk of the semiconductor, which reveals itself as a voltage-dependent current. The details of the nonequilibrium distribution depend on the elastic and Andreev scattering at the superconductor-semiconductor interfaces. We find that the elastic scattering at the interfaces is dominated by Fermi-momentum mismatch.

The experimental system studied is shown in Fig. 1(a). It consists of a thin silicon membrane sandwiched between two niobium electrodes. The membrane is obtained[11] by locally etching through a silicon wafer with a degenerately B-doped surface layer (doping level about 8×10^{19} cm^{-3}). A shallow implantation is applied to ensure that the thickness of the doped layer is about 50 nm. A wet anisotropic etch is used which stops at the doped surface layer. The result is a very thin slice of heavily doped, single-crystalline silicon, which is uniform to within 10 nm over the entire surface of 900 μm^2. The accessible size of the crystal is varied by opening a contact window in the insulating layer on top of the membrane, using standard photolithograpy. The main experimental results reported here do not depend on the area, which has been varied from 1 to 600 μm^2. After opening the window, the silicon surface is thoroughly cleaned using standard chemical methods, leaving a hydrogen-passivated surface. Subsequently, the sample is brought into a UHV chamber and covered on both sides with 300-nm-thick electron beam-evaporated niobium.

In Fig. 2(a) a typical current-voltage (I-V) characteristic for a 35-μm^2 sample, measured at a temperature of 1.2 K, is shown. A large number of samples of various sizes have been studied all showing the same general pattern. For high voltages, above a few millivolts one finds a linear slope which intercepts the vertical axis at negative current values. This phenomenon has been reported in previous work on coplanar devices with silicon and In-Ga-As and is generally called a current deficit.[12,13] In addition, a clear signature of the superconducting energy gap of niobium at voltages of 2.8 mV or lower is found. Expanding the current and voltage axis around the origin a supercurrent is revealed up to a critical value I_c [see inset Fig. 2(a)]. The application of a magnetic field B results in $I_c(B)$ characteristics displaying the well-known Fraunhofer diffraction pattern for superconducting Josephson junctions.

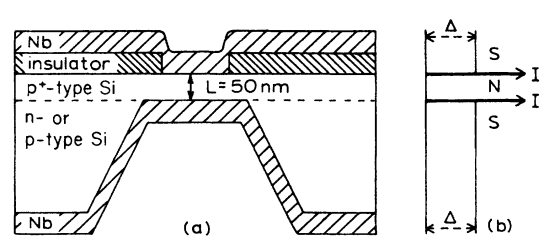

FIG. 1. (a) Niobium-silicon-niobium contact based on a single-crystal silicon membrane. (b) Energy diagram for current transport through the niobium-silicon-niobium contact. Interface potential (I), bulk silicon (N), superconductor (S).

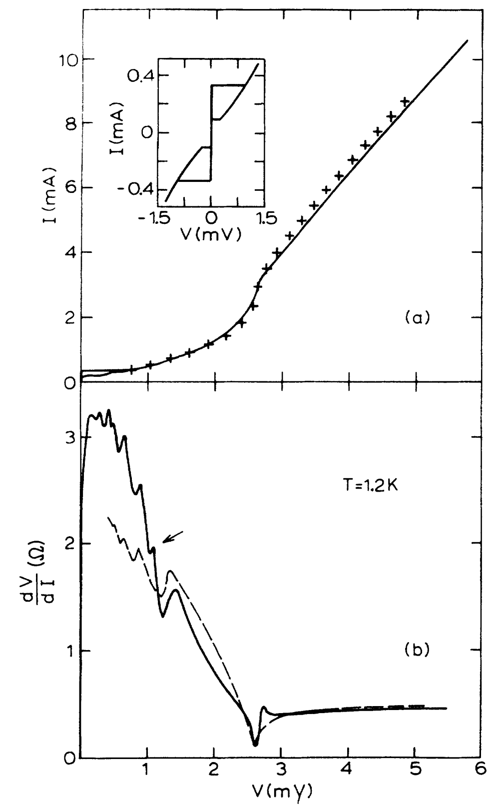

FIG. 2. (a) Current and (b) differential resistance as a function of voltage for a sample with an area of 35 μm^2, measured at a temperature of 1.2 K. The inset in part (a) of the figure shows on an expanded scale the observed supercurrent. Crosses and the dashed line represent the predictions of the *S-I-N-I-S* model with $Z=2.0$. Subharmonic gap structure at $eV=2\Delta/n$, with $n=1-6$ is clearly visible. The origin of the structure marked with an arrow is unknown. It is absent in most other samples.

In the present paper we focus on the current-transport processes occurring when a voltage is applied. Using standard free-electron parameters and a drift mobility of 0.01 m^2/Vs for Si, a mean free path for elastic scattering of about 5 nm is obtained, indicating that the carriers undergo some elastic scattering in the bulk of the silicon. For the sample shown in Fig. 2(a) the high-voltage differential resistance is about 0.46 Ω. Based on the doping level and the geometry, we estimate that the silicon layer itself has a resistance below 16 mΩ. In all our samples the bulk resistance amounts to less than 3% of the actual observed differential resistance. Hence, we assume that the observed resistance is entirely dominated by the two niobium-silicon interfaces.

Below 3 mV details of the current-voltage characteristics are more clearly shown in the differential resistance as a function of voltage [Fig. 2(b)]. Apart from a dip at twice the energy gap of niobium at 2.8 mV, we also find minima in dV/dI at voltages roughly equal to $2\Delta_{Nb}/ne$, with $n=2$, 3, 4, 5, and 6. Δ_{Nb} is the superconducting energy gap of Nb. This structure has been extensively studied in microbridges and is generally called the subharmonic energy-gap structure (SGS). The highest order that is observed varies from sample to sample, with n ranging from at least 2 to at most 6. Its relation to the gap has been verified by measuring its temperature dependence. For increasing temperature, the measured position of the dips follows the BCS temperature dependence of the gap closely.

The presence of a current deficit and of subharmonic gap structure is implied in a theoretical model presented by Octavio *et al.*[14] Originally introduced to capture the influence of elastic scattering on the current-voltage characteristics of superconducting microcontacts, the model, as we will show, matches precisely the physical situation encountered in semiconductor-coupled superconductors. It describes a superconductor-normal-metal-superconductor structure with only elastic scattering at the interfaces, represented by δ-function potential of variable height, expressed in a dimensionless parameter Z [cf. Fig. 1(b)]. In this so-called *S-I-N-I-S* model, where *I* represents the barrier at the interface, it is assumed that both elastic and inelastic scattering are absent in the normal metal between the two interfaces.

With these assumptions, the "hot" quasiparticles in *N* can be separated into two subpopulations, depending on their direction of motion, $f_{\rightarrow}(E)$ and $f_{\leftarrow}(E)$. At the interfaces both elastic and Andreev scattering occur, their relative magnitude depending on the barrier strength Z. Using the appropriate boundary conditions at the interfaces and symmetry arguments one has the following expression for the energy distribution:[15]

$$f_{\rightarrow}(E)=A(E)f_{\rightarrow}(E-eV)+B(E)[1-f_{\rightarrow}(-E-eV)] +T(E)f_0(E)\,. \tag{1}$$

$A(E)$, $B(E)$, and $T(E)$ are the coefficients of Andreev reflection, normal reflection, and transmission, respectively.[14] $f_0(E)$ represents the equilibrium Fermi distribution. The applied voltage V is equally distributed over the two interfaces. The population of quasiparticles traveling to the right is determined by a transmitted part due to the equilibrium reservoir, an Andreev-reflected part resulting from incident holes and a normal-reflected part resulting from incident electrons. Solving Eq. (1) self-consistently, the current through the junction can be obtained from

$$I=(eR_n)^{-1}\int dE[f_{\rightarrow}(E)-f_{\leftarrow}(E)]\,, \tag{2}$$

with $R_n=(1+2Z^2)R_s$, the normal-state resistance due to the two barriers at the interfaces. R_s is the Sharvin resistance, which equals $1/2N(0)e^2v_FA$, with $N(0)$ the single-spin density of states, v_F the Fermi velocity, and A the area of the contact. In Fig. 2(a) the *I-V* curve predicted by this model is shown for $Z=2$ (crosses). The current at high voltages falls below the value expected for the normal state. The differential resistance, Fig. 2(b), clearly shows structure at submultiples of the gap due to multiple Andreev reflections. Within the model both features are due to a voltage-induced nonequilibrium population of electron states in the normal region, which in our experiment means the bulk of the semiconductor. As can be seen from Fig. 2, the measured *I-V* and *dV/dI-V* characteristics are very well reproduced by this *S-I-N-I-S* model, with Z as the only free parameter.

A further check is provided by the differential conductance at zero voltage. In samples with $I_c = 0$ or by quenching the supercurrent with a magnetic field we study the temperature dependence of the conductivity (Fig. 3). For $Z^2 > 1$ the temperature dependence of dI/dV is to a fairly good approximation determined by the reflection and transmission coefficients through

$$\frac{dI}{dV} = \frac{Z^2}{R_n} \int \left[-\frac{\partial f_0(E)}{\partial E} [1 + A(E) - B(E)] \right] dE . \quad (3)$$

In Fig. 3 this expression is shown, together with measurements for a 10-μm^2 sample. Reasonable agreement is obtained by taking $Z = 3.5$, while for the same sample a value of about 3.2 is found from a comparison of the I-V curve at high voltages. Note that dI/dV does not diverge at low temperatures, as would be expected for a tunnel barrier, due to the presence of Andreev reflection.

For samples produced in different runs values for Z are found ranging from 1.7 to 8.0. This variation may be caused by variations in the condition of the silicon surface just before Nb deposition. To prevent damage of the membranes no *in situ* cleaning can be performed and some contamination of the silicon surface before niobium deposition might occur. On the other hand, the scattering at the interface may also be due to a very thin Schottky barrier, which dependence on doping concentration has been studied.[16] However, extrapolation of the standard Schottky theory[17] to the high doping levels used in the present experiment requires extremely thin barriers of about 2.8 nm, comparable to the spacing of the doping atoms (2.2 nm). Hence, large statistical fluctuations must be present invalidating the use of standard continuum Schottky theory.

Within the assumptions of the model, Z must also determine the normal-state resistance, since only scattering at the interfaces is taken into account. Based on Z, for the contact resistance a lower value of 10^{-12} $\Omega\,\mathrm{m}^2$ is found, a factor of 3–50 lower than the experimentally observed values. Apparently, only a fraction of the interface has the high transparency inferred from the details of the conduction process. We tentatively attribute this to variations in the electronic properties of the interface due to the fabrication conditions.

The lowest value of $Z = 1.7$ may be indicative of a nearly ideal interface. It implies that approximately 25% of the electrons incident at the barrier will be transmitted, which is an extremely high transparency. Based on Fermi-momentum mismatch one expects[18] for p-type Si with a Fermi energy of 0.1 eV a minimum value for Z on the order of 1.7–2.4, in fair agreement with the observed lower value of 1.7. Consequently, the scattering potential at the interface is likely to have an intrinsic origin. The presence of such an intrinsic "mismatch barrier" will set an upper limit to the transmission of any superconductor-semiconductor interface, and, consequently, reduces the supercurrent in a S-SM-S structure. It will also strongly influence the formation of a discrete excitation spectrum due to Andreev reflections.[6–9] For the Z values we find (on the order of 2) the Andreev reflection coefficient $A(E)$ is reduced to 0.01.

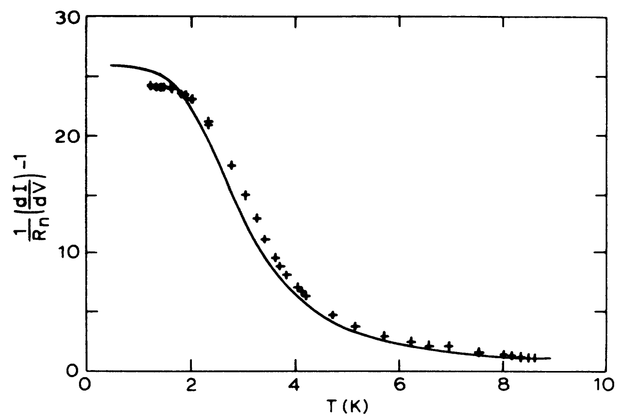

FIG. 3. Normalized differential resistance around $V = 0$ vs temperature. Crosses indicate experimentally measured values and the line indicates the predictions of the S-I-N-I-S model using $Z = 3.5$.

In conclusion, we have demonstrated that the current-voltage characteristic of silicon-coupled superconducting electrodes can be understood in detail by assuming only Andreev and elastic scattering at the interfaces and ignoring scattering in the bulk of the silicon. Since phase breaking is closely related to energy relaxation, this implies that phase coherence is possibly maintained throughout the conduction process, questioning the validity of the Boltzmann-equation approach taken in Eqs. (1)–(3). Although the present analysis appears to be adequate, we believe that a systematic study of phase coherent effects is currently within reach in these S-SM-S systems.

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[1] T. D. Clark, R. J. Prance, and A. D. C. Grassie, J. Appl. Phys. **51**, 2736 (1980).

[2] T. Nishino, M. Miyake, Y. Harada, and U. Kawabe, IEEE Electron Device Lett. **EDL-6**, 297 (1985).

[3] H. Takayanagi and T. Kawakami, Phys. Rev. Lett. **54**, 2449 (1985).

[4] Z. Ivanov, T. Claeson, and T. Anderson, Jpn. J. Appl. Phys. **26**, 1617 (1987).

[5] J. Seto and T. van Duzer, in *Low Temperature Physics LT13*, edited by K. D. Timmerhaus, W. J. O'Sullivan, and E. F. Hammel (Plenum, New York, 1974), p. 328.

[6] I. O. Kulik, Zh. Eksp. Teor. Fiz. **57**, 1745 (1969) [Sov. Phys. JETP **30**, 944 (1970)].

[7] J. Bardeen and J. L. Johnson, Phys. Rev. B **1**, 72 (1972).

[8]B. J. van Wees, K.-M. H. Lenssen, and C. J. P. M. Harmans, Phys. Rev. B **44**, 470 (1991).

[9]A. Furusaki, H. Takayanagi, and M. Tsukada, Phys. Rev. Lett. **67**, 132 (1991).

[10]C. W. J. Beenakker and H. van Houten, Phys. Rev. Lett. **66**, 3065 (1991).

[11]W. M. van Huffelen, M. J. de Boer, and T. M. Klapwijk, Appl. Phys. Lett. **58**, 2438 (1991).

[12]D. R. Heslinga, W. M. van Huffelen, and T. M. Klapwijk, IEEE Trans. Magn. **27**, 3264 (1991).

[13]A. W. Kleinsasser, T. N. Jackson, D. McInturff, F. Rammo, G. D. Pettit, and J. M. Woodall, Appl. Phys. Lett. **57**, 1811 (1990).

[14]M. Octavio, M. Tinkham, G. E. Blonder, and T. M. Klapwijk, Phys. Rev. B **27**, 6739 (1983); T. M. Klapwijk, *SQUID '85 —Superconducting Quantum Interference Devices and Their Applications,* edited by H. D. Hahlbohm and H. Lübbig (Walter De Gruyter & Co., Berlin, 1985).

[15]K. Flensberg, J. Bindslev Hansen, and M. Octavio, Phys. Rev. B **38**, 8707 (1988).

[16]D. R. Heslinga and T. M. Klapwijk, Appl. Phys. Lett. **54**, 1048 (1989).

[17]S. M. Sze, *Physics of Semiconductor Devices,* 2nd ed (Wiley, New York, 1981).

[18]P. C. van Son, D. R. Heslinga, W. M. van Huffelen, and T. M. Klapwijk (unpublished).