Phase-periodic proximity-effect compensation in symmetric normal/superconducting mesoscopic structures

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(Received 8 September 1997; revised manuscript received 9 January 1998)

The conductance (G) of mirror-symmetric, disordered normal (N) metal mesoscopic structures with two interfaces to superconductors (S) has been studied experimentally with applied condensate phase differences $\Delta\phi$ between the N/S interfaces. At $\Delta\phi=2n\pi(n=0,1,2,3,...)$ the conductance showed reentrance to the normal state below the temperature corresponding to the Thouless energy. The current-voltage characteristics were found to be strongly nonlinear even at distances between the N/S interfaces largely exceeding the normal-metal coherence length. An influence of superconductors almost completely disappeared at $\Delta\phi=(2n+1)\pi$ where the structures showed normal behavior. Calculations based on a quasiclassical theory have been performed offering a quantitative explanation of such a phase-periodic reentrance. The value of the superconducting gap $\Delta_{\rm eff}$ at the Ag/Al interface has been obtained. We find that $\Delta_{\rm eff}(T,V\rightarrow 0)=\beta\cdot\Delta_{\rm BCS}(T)$ with $\beta=0.2$ independent of temperature in the temperature interval of $0.1\ {\rm K}<T<1.6\ {\rm K}$; $\Delta_{\rm BCS}(T)$ is the BCS gap vs T function in Al. [S0163-1829(98)01746-9]

The conductance of a normal (N) disordered mesoscopic structure with interfaces to superconductors (S), oscillates as a function of the condensate phase difference, $\Delta\phi$, between the latter.[1,2] The amplitude of oscillations exceeds the value of e^2/h by several orders of magnitude at unexpectedly large distances between the N/S interfaces,[3] i.e., it is not related to the weak localization corrections as it was anticipated previously.[4] Recently, several theoretical works[5–8] have proposed an explanation for such ''giant'' oscillations, taking into account the characteristic energy dependence of the condensate wave function on the N side and its contribution to the conductance of the normal structure (proximity effect). Remarkably, the contributions, interpreted as the Cooper pair penetration and the change in the density of states on the N side,[9] cancel each other at low energies of quasiparticles. As a result, the influence of the superconductors disappears at low enough temperatures, leading to a ''reentrant'' behavior of the normal structure.[10] The giant oscillations appear as a result of the dependence of the condensate wave functions on the phase difference between the N/S boundaries and their amplitude is predicted to be a nonmonotonic function of temperature (''thermal effect,'' following terminology of Ref. 5) and/or voltage bias.[6] An experimental observation of the thermal effect in the phase periodic conductance of N/S structures with T-shaped normal parts has been reported in Ref. 11.

Another extraordinary prediction by the theory is a complete absence of the influence of superconductors on the electron transport at phase difference between the superconductors of $\Delta\phi=\pi$ in disordered structures of certain symmetry. That is the case, for example, in N/S mesoscopic structures of mirror symmetry when the classical current lines lie in the mirror plane relating N/S interfaces. The theory predicts *normal behavior* at a phase difference between the superconductors of $\Delta\phi=\pi$, with the temperature dependences of the conductance and current-voltage characteristics of normal parts of such symmetrical structures to be identical to those in the *absence* of superconductors.[5] We emphasize that the phase-coherent effects exist and the condensate contribution to the conductance periodically disappears even when the distance between the N/S interfaces greatly exceeds the coherence length ξ_N of normal quasiparticles and Josephson currents are negligible [$\xi_N=(\hbar D/2\pi k_B T)^{1/2}$, D is the diffusion coefficient of conduction electrons]. The effect is due to the fact that in mesoscopic structures Cooper pairs which contribute to the con-

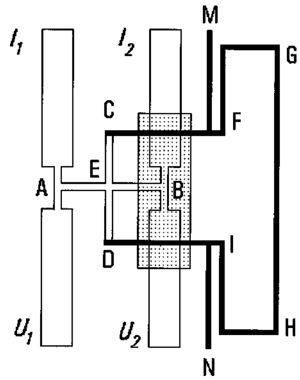

FIG. 1. The geometry of the structures. The resistance of normal (silver) wire *AB* with interfaces to superconducting (aluminum) loop *CFGHID* at points *C* and *D* has been measured with potential leads U_1-U_2 and current leads I_1-I_2. A spacer of Al_2O_3 provides electrical insulation between the loop and the leads. Dimensions are given in the text.

ductance penetrate into the normal conductor over a large distance comparable to the dimension of the structure. In the structures with two N/S interfaces the condensate contribution to the conductance consists of two parts caused by each N/S interface. These parts compensate each other in a symmetric system at $\Delta\phi=\pi$.

We report an experimental study of the influence of the phase difference, $\Delta\phi$, on the current-voltage characteristics in symmetric mesoscopic N/S structures with crosslike normal regions, suggested in Ref. 1. One normal wire connects superconductors while the current flows in the perpendicular direction (Fig. 1). The temperatures were high enough so that the Josephson critical current was negligible and the resistance of the normal wires was finite. The conductance at $\Delta\phi=0$ showed reentrant behavior. The current-voltage characteristics at $\Delta\phi=0$ were found to be strongly nonlinear and highly temperature dependent below the superconducting transition. The behavior of the structures at $\Delta\phi=\pi$ was found to be drastically different: the current-voltage characteristics were close to linear with temperature-independent conductance close to that in the absence of superconductivity. A phase flip of oscillations in the differential conductance at high bias voltages has been observed. No excess, or deficit, current at high voltage has been detected. The observations are analyzed in the framework of a quasiclassical theory[5–8] in which the Usadel equation[12] is significant.

Our structures consisted of a normal conductor in the shape of a cross to which a superconducting wire was attached at two points as shown in Fig. 1. The superconducting wire had the shape of a rectangular loop. An insulating spacer of Al_2O_3 was placed between the superconducting wire and the current and potential leads to prevent electrical contact. The phase difference between the N/S interfaces at points *C* and *D* was created by applying a magnetic-field perpendicular to the structure or, alternatively, by passing a control current through the superconductor. Using the four-terminal method, we measured the differential resistance, dV/dI, and the total resistance, R_{AB}, of the normal part *AB* using measuring leads I_1, I_2, U_1, U_2. We performed dc as well as low-frequency ac measurements using lock-in and modulation techniques in the frequency range of 30–300 Hz in magnetic fields of less than 100 G obtained using an electromagnet. The measurements have been done at temperatures in the range from 0.1 to 1.7 K. The Al loop was in the superconducting state below 1.4 K. The reason for the nonzero resistance values at $0.7\,\mathrm{K}<T<1.3\,\mathrm{K}$ seen in Fig. 4 is that the data was taken using two normal-metal leads in a series with the loop.

The normal, insulating, and superconducting layers of the structures were fabricated using the ''lift-off'' electron lithography technique. The first layer was a normal part made of a 40 nm thick and 100 nm wide silver film. The second and the third layers were 20 nm thick insulator (Al_2O_3) and 40 nm thick aluminum films, respectively. The *C* and *D* ends of the silver cross were etched by an Ar ion beam before the deposition of the aluminium strip. The area of the N/S interface was about $100\times200\,\mathrm{nm}^2$. The distance between the normal leads, $L_N=AB$, was equal to 2000 nm with $AE=EB=L=1000$ nm. The distance between the N/S interfaces, $L_S=CD$, varied from 500 to 2000 nm (with $CE=ED$) for different samples (see Table I). The precision of the alignment of different layers was better than 100 nm. The substrate was silicon covered by its native oxide.

The value of the diffusion coefficient of conduction electrons in silver *D* calculated using the measured value of the resistance was equal to about $80\,\mathrm{cm}^2/\mathrm{s}$ and the coherence length $\xi_N=300$ nm for the lowest temperature in our experiment. The phase breaking length of electrons L_ϕ in silver was estimated to be approximately 1500 nm using weak-localization measurements in long coevaporated wires. Special attention was paid to the measurements of the resistance of Ag/Al interfaces and of different parts of the structure using different combinations of the leads for potential and current. Using such measurements we also found that the deviations from the symmetry of the structure with respect to the center of the cross were within 10% measurement error.

TABLE I. Parameters and amplitudes of zero-bias resistance oscillations for three Ag samples with Al mirrors. L_N, length of normal (Ag) arm. L_S is the length of perpendicular Ag arm between (Al) superconductors. R_N is the normal resistance of *AB* strip. ρ, resistivity of Ag. *D* is the diffusion coefficient of electrons in Ag. *l* is the electron mean free path in Ag strip. *r*, exp. is the measured relative resistance of N/S interfaces. *r*, theor. is the relative resistance of N/S interfaces used to fit the theory and experiment. $\Delta R/R$ is the amplitude of resistance oscillation.

Sample	L_N (μm)	L_S (μm)	R_N (Ω)	ρ ($\mu\Omega$ cm)	D (cm^2/s)	l (nm)	r, exp.	r, theory	$\Delta R/R$, exp.	$\Delta R/R$, theor.
1	2.0	0.5	10.5	2.11	84	25.4	1.4	1.4	7.3	7.3
2	1.0	1.0	6.1	2.46	72	21.8	1.1	1.1	5.2	3.8
3	2.0	2.0	10.8	2.16	82	24.8	1.4	1.4	1.6	1.0

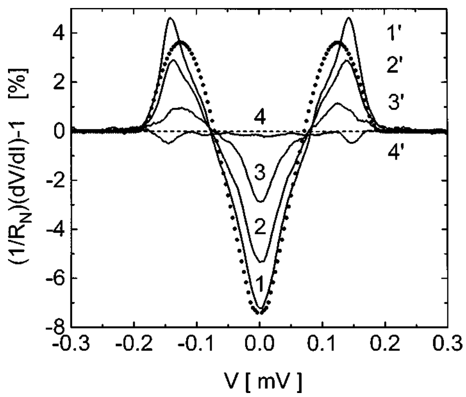

FIG. 2. Normalized differential resistance of sample 1 versus applied dc voltage at different superconducting phase differences. 1-1′: $\Delta\phi=0$; 2-2′: $\Delta\phi=0.6\pi$; 3-3′: $\Delta\phi=0.8\pi$; 4-4′: $\Delta\phi=\pi$, $T=0.58$ K. The phase difference was varied by a magnetic field and its value determined from the 2π periodicity. Dotted and dashed lines are theoretical curves for $\Delta\phi=0$ and $\Delta\phi=\pi$, respectively.

We have found the resistance of the N/S barriers to be of the order of the resistance of the normal wires (see Table I).

The I-V curves appeared to be very sensitive to the current through the superconducting wire and/or magnetic flux through the loop. Figure 2 shows the differential resistance (dV/dI) of the normal part of the structure vs dc bias voltage between the points A and B (see Fig. 1), at different magnetic fluxes in the absence of superconducting current through aluminium wire. It is seen that the curves are nonlinear with a drop in the resistance at zero bias when no magnetic field is applied. At higher fields the curves flatten and become close to linear at a field at which the phase difference $\Delta\phi=\pi$ between the points C and D. The changes were periodic with a period $\Delta H=\Phi_0/S$, $\Phi_0=h/2e$, S is the area of the loop $CFGHD$.

Oscillations in dV/dI as a function of magnetic flux at different bias voltages are shown in Fig. 3. It is seen from Figs. 2 and 3 that $\Delta\phi=\pi$ is, indeed, a very special point. The structure is less sensitive to the applied voltage at that phase difference. Furthermore, the resistance R_{AB} at $\Delta\phi=\pi$ is found to be equal to the resistance in the absence of

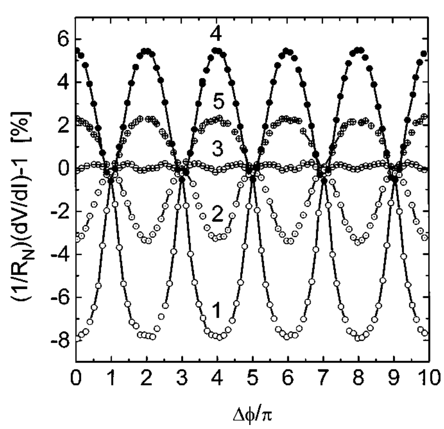

FIG. 3. Normalized diffferential resistance of sample 1 as a function of superconducting phase difference at different applied dc voltages. (1) $V=0$; (2) $V=0.045$ mV; (3) $V=0.08$ mV; (4) $V=0.14$ mV; (5) $V=0.17$ mV; $T=0.58$ K.

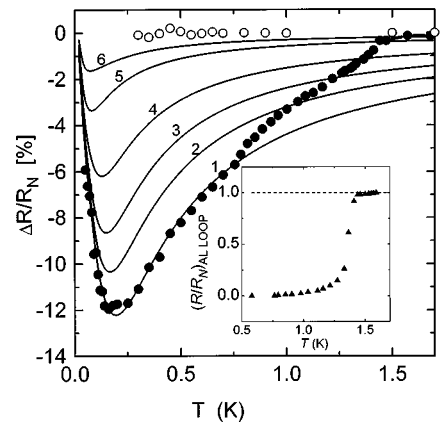

FIG. 4. Zero-bias resistance for the AB arm as a function of temperature at $\Delta\phi=0$ (filled circles) and $\Delta\phi=\pi$ (open circles) for sample 1. The resistance of the superconducting loop (triangles) is also given in the inset. Solid lines are theoretical curves for $\Delta\phi=0$ for different values of the superconducting gap at the N/S interface, Δ_{eff}. (1) $\Delta_{\mathrm{eff}}=0.051$ meV; (2) $\Delta_{\mathrm{eff}}=0.045$ meV; (3) $\Delta_{\mathrm{eff}}=0.039$ meV; (4) $\Delta_{\mathrm{eff}}=0.033$ meV; (5) $\Delta_{\mathrm{eff}}=0.027$ meV; (6) $\Delta_{\mathrm{eff}}=0.021$ meV. For $\Delta\phi=\pi$ the calculated value of $R=\mathrm{const}=R_N$, $\Delta R=0$.

superconductivity in the aluminium wire. The latter can be seen from Fig. 4, where the total resistance R_{AB} at zero bias and $\Delta\phi=0$ and π is shown as a function of temperature. The changes in the resistance at $\Delta\phi=\pi$ are by more than an order in magnitude less than at $\Delta\phi=0$ and are close to that in the coevaporated silver wires with no interfaces to superconductors within the given temperature interval. Similar effects were observed when the phase difference $\Delta\phi$ was changed by the control current in the superconducting wire. The oscillations as a function of control current through the superconducting wire MN had a period of $\Delta I=26\ \mu$A. Using the following equation for the phase difference in the absence of an external magnetic field:

$$\Delta\phi=2\pi(\mathcal{L}/\Phi_0)I,$$

we can calculate the effective self-inductance of the superconducting loop $\mathcal{L}$, which is the sum of the "kinetic" and "geometric" contributions (see, e.g., Ref. 1). For our S-loop we find $\mathcal{L}=0.8\times10^{-10}$ H.

An additional feature of the oscillations is the phase flip, where a minimum in the resistance is replaced by a maximum, occurring at voltages corresponding to the states with $dV/dI>R_N$ (see Figs. 3 and 2). At the crossover voltage itself, which in this case was about 0.07 mV, the second harmonic of oscillations survives, while the regular period is suppressed. The oscillations show strongly nonsinusoidal shapes at the lowest temperatures investigated. No hysteresis was detected.

Figure 4 shows the dependence of the zero-bias resistance for the AB arm as a function of temperature at $\Delta\phi=0$ and $\Delta\phi=\pi$ for sample 1. The resistance at $\Delta\phi=0$ starts to decrease at the onset of superconductivity of the superconducting loop showing a minimum as a function of temperature followed by a steep increase (the reentrant behavior). The resistance for the AB arm at $\Delta\phi=\pi$ is temperature independent within experimental error.

The phase periodic conductance oscillations can be ascribed to a condensate contribution to the conductance. The amplitude of the induced condensate depends on the phase difference $\Delta\phi$ turning to zero at $\Delta\phi=\pi$. This effect can be understood in terms of Andreev reflections at the N/S interfaces.[13] During Andreev reflection, an electron transforms into a hole acquiring an extra phase ϕ equal to the phase of the superconducting condensate and *vice versa*; a hole transforms into an electron gaining an extra phase $-\phi$. The conductance of a normal conductor oscillates as a function of the phase difference $\Delta\phi$ between two superconducting banks due to the fact that a fraction of the electrons is reflected as holes from both N/S interfaces, rather than one particular interface. The quantum interference results in a 2π periodicity of $\Delta\phi$ and goes from constructive at $\Delta\phi=0,2\pi,\ldots$ to destructive at $\Delta\phi=\pi,3\pi,\ldots$. The net effect of the destructive interference of Andreev reflected quasiparticles is that the resultant amplitude of the Andreev reflected hole (electron) is decreased, which is equivalent to a decrease in the probability of Andreev reflection and, hence to a decrease in the proximity correction to the conductance. To describe the phenomenon quantitatively deeper analysis is required.

According to the microscopic theory, the current across the normal part may be written as[5–8]

$$I(V,T)=(1/eR_N)\int_0^\infty F(\varepsilon,V,T)[1-m(\varepsilon)]d\varepsilon, \qquad (1)$$

where $2V$ is the dc voltage applied to the N part, $F(\varepsilon,V,T)=1/2\{\tanh[(\varepsilon+eV)/2k_BT]-\tanh[(\varepsilon-eV)/2k_BT]\}$ is the difference in equilibrium distribution functions in the normal reservoirs, and R_N is the resistance of the N part in the absence of superconductors. The energy-dependent function $m(\varepsilon)$ determines the correction to the conductance due to the proximity of superconductors. In a diffusive regime $m(\varepsilon)$ can be calculated using the Usadel equation.[12] For a general nonsymmetric geometry with $L_1=L_{CE}$, $L_2=L_{ED}$, $L=L_{AB}/2$, in the linear approximation (weak proximity effect) the result can be written as

$$m(\varepsilon)=A(\varepsilon)+B(\varepsilon)\cos\Delta\phi, \qquad (2)$$

where

$$A(\varepsilon)=(-1/16)\{\mathrm{Re}(C_x^2+C_y^2)[\sinh(2\theta)/2\theta-1]-[|C_x|^2+|C_y|^2][\sinh(2\theta')/2\theta'-\sin(2\theta'')/2\theta'']\}, \qquad (3)$$

$$B(\varepsilon)=(1/16)\{\mathrm{Re}(C_x^2-C_y^2)[\sinh(2\theta)/2\theta-1]-[|C_x|^2-|C_y|^2][\sinh(2\theta')/2\theta'-\sin(2\theta'')/2\theta'']\}. \qquad (4)$$

Here

$$C_{x,y}=(1/\theta)[r_1F_{s1}/\cosh\theta_1\pm r_2F_{s2}/\cosh\theta_2]\times\{[\sinh\theta\sinh(\theta_1+\theta_2)]/(\cosh\theta_1\cosh\theta_2)+2\cosh\theta\}^{-1}. \qquad (5)$$

F_{s1} and F_{s2} are the equilibrium condensate Green's functions in the superconductor terminals: $F_{s1,2}=\Delta_{1,2}/[(\varepsilon+i\Gamma_{1,2})^2-\Delta_{1,2}^2]^{1/2}$; $\Delta_{1,2}$ are superconducting gaps at the N/S interfaces, which are assumed to be voltage-independent constants; $\theta=\theta'+i\theta''=kL$, $\theta_{1,2}=kL_{1,2}$, $k=[(2i\varepsilon+\gamma)/hD]^{1/2}$, $\gamma=hD/L_\phi^2$ is the phase-breaking rate in the normal wire, $\Gamma_{1,2}$ are depairing rates in the superconductors, and $r_{1,2}=R_N/2R_{1,2}$, $R_{1,2}$ being the total resistance of $N/S_{1,2}$ interfaces, correspondingly.

According to Eqs. (3) and (4) the values of $A(\varepsilon)$ and $B(\varepsilon)$ *both* become vanishingly small at low enough energies and the conductance should approach the normal-state value (''reentrance'' [10,14]) independently of the phase difference. Various theoretical approaches, including the scattering-matrix method based on the generalized Landauer formula with Andreev reflections taken into account[15] and the numerical solution of the Bogolubov–de Gennes equations,[6] as well as previous calculations based on the equations for the quasiclassical Green's functions,[5,7] show that such behavior is general for mesoscopic N/S structures.

Formulas (2)–(5) reduce to simpler ones in specific cases (e.g., by putting $\Delta_2=0$ and $L_2=0$ for a ''quantum trombone'' geometry[17]). In the case of mirror symmetry, i.e., $L_1=L_2$, $\Delta_1=\Delta_2=\Delta$, $r_1=r_2=r$, and $\Gamma_1=\Gamma_2=\Gamma$, we find that $A(\varepsilon)=B(\varepsilon)$ and Eq. (2) reduces to[5,6,8]

$$m(\varepsilon)=(1/16)(1+\cos\phi)r^2\{\mathrm{Re}[F_S^2/(\theta\cosh\theta(1+L_1/L))^2]\times[(\sinh(2\theta)-2\theta)/\theta]-|F_S|^2/|\theta\cosh\theta\times(1+L_1/L)|^2[\sinh(2\theta')/\theta'-\sin(2\theta'')/\theta'']\}, \qquad (6)$$

where $F_S^2=\Delta^2/[\Delta^2-(\varepsilon+i\Gamma)^2]$.

It follows from Eq. (6) that $m(\varepsilon)=0$ for any ε at the phase difference $\Delta\phi=\pi$, and the system responds to the voltage bias and temperature [see Eq. (1)] as if there were no superconductors. The situation corresponds to the total compensation of the nonoscillating contribution $A(\varepsilon)$, which is believed to be a result of the contribution of electrons independently reflected at different interfaces by the interference term $B(\varepsilon)$. The latter describes the interference contribution of electrons (holes) reflected as holes (electrons) from *both* banks. That explains our results for measurements at $\Delta\phi=\pi$.

Considering the value of Δ as a phenomenological fitting parameter Δ_{eff}, in formulas (1)–(6) we were able to explain our results quantitatively. Figure 5 shows the experimental dependence of $\Delta_{\mathrm{eff}}(T,V\to0)$ at zero bias calculated from the data presented in Fig. 4 using the fact that the position of the minimum of the resistance at $\Delta\phi=0$ is sensitive to the value of the gap at the N/S interface. The value of $\Delta_{\mathrm{eff}}(T,V\to0)$ is normalized to the value $\Delta_{\mathrm{eff}}(T\to0,V\to0)=0.051$ meV, calculated using the experimental value of the critical temperature of the Al loop. The rest of the fitting parameters, including the diffusion coefficient, the phase-breaking length, the depairing rate, and the resistance of the N/S barriers were taken as temperature independent with their values in reasonable agreement with those from direct measurements (see Table I). By introducing a scatter in the values of the fitting parameters during calculations we estimated the error in the determination of the *absolute* value of $\Delta_{\mathrm{eff}}(T,V\to0)$ as ±0.015 meV. The solid line in Fig. 5 is the BCS gap $\Delta_{\mathrm{BCS}}(T)$, as a function of temperature normalized to the ''bulk'' zero-temperature value, $\Delta_{\mathrm{BCS}}(0)$. We find that $\Delta_{\mathrm{eff}}(T,V\to0)=\beta\cdot\Delta_{\mathrm{BCS}}(T)$ with $\beta=0.2$ independent of temperature in the temperature interval investigated. Computer

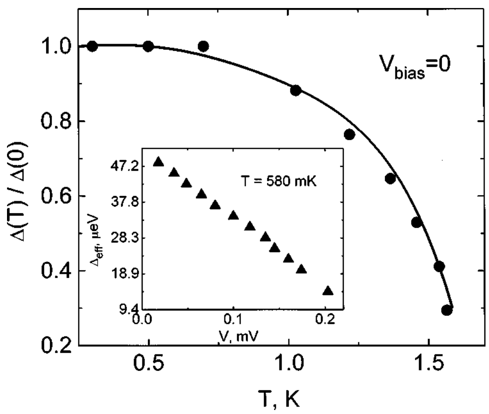

FIG. 5. The dependence of the superconducting gap $\Delta_{\rm eff}$ at the Ag/Al interfaces for sample 1 on temperature (circles) obtained from the fit of experimental zero-bias curves to the theory. The gap values are normalized to the extrapolated zero-temperature value, $\Delta_{\rm eff}(0)=0.051$ meV. The solid line is the BCS gap as a function of temperature normalized to the ''bulk'' zero-temperature value, $\Delta_{\rm BCS}(0)=0.24$ meV. Inset: the dependence of $\Delta_{\rm eff}$ on applied dc voltage at temperature $T=0.58$ K obtained using fit of the theory with experimental curves.

simulations using formula (2) show that the procedure described can be used to determine the value of the effective gap $\Delta_{\rm eff}\leqslant 5hD/L_1^2$. At larger values of the gap the position of the resistance minimum is determined by the value of the Thouless energy, $\varepsilon_{\rm Th}=hD/L_1^2$.

The dependence of the amplitude of the phase-periodic oscillations on the distance between the N/S interfaces at low voltages is also in fairly good agreement with the calculations based on formulas (1) and (6). Substituting experimental parameters into Eqs. (6) and (1) we find zero-bias resistance amplitudes of 1.0, 3.8, and 7.3% at $T=0.58$ K for our three samples with $CE=DE=L_1=2$, 1, and 0.5 μm, with corresponding experimental values of 1.6, 5.2, and 7.3% (see Table I).

The inset in Fig. 5 shows the dependence of $\Delta_{\rm eff}$ on the bias voltage obtained from the fit of the $dV/dI-V$ curves at $T=580$ mK shown in Fig. 2. We emphasize that the observed strong dependence of the gap on voltage cannot be explained by the heating of the sample. Using experimental data[16] for the energy relaxation length L_ε, we have calculated the upper limit for an increase ΔT in the electron temperature in the middle of the sample using a model[18] and found $\Delta T\approx 0.5$ K at $T=0.6$ K, $V=0.2$ mV, $L_\varepsilon=6$ μm, for our geometry. According to the direct temperature dependence measurements at zero bias (Fig. 5) such an increase in the electron temperature would lead to 10% decrease in $\Delta_{\rm eff}$, which is much less than the experimentally observed suppression of the gap. That may suggest that an assumption that the energy gap in the superconductor is a voltage-independent constant is not true. The latter may be due to high transmittance of the S/N interface. The effective gap $\Delta_{\rm eff}$ near the S/N interface must be determined from the self-consistency equation taking into account the nonequilibrium distribution function on both sides of the N/S interface. Two more questions to be addressed by the theory are the nonsinusoidal line shape of oscillations at low temperatures and the deviation of the $dV/dI-V$ characteristic for $\Delta\phi=\pi$ from a constant value at high biases.

In conclusion, we find that the influence of superconductors on the electron transport in hybrid normal/superconducting disordered cross-shaped structures of mirror symmetry with two superconducting banks leads to considerable changes in the conductance. Nonlinear current-voltage dependences are noted even when the distance between the N/S interfaces greatly exceeds the coherence length of normal quasiparticles, which is consistent with existing experimental data.[3] The influence of superconductors on the transport in the normal arm of the cross depends drastically on the phase difference $\Delta\phi$ between the N/S interfaces and is practically absent at $\Delta\phi=\pi$. Theoretical calculations have been performed, explaining the observed *normal behavior* at $\Delta\phi=\pi$, in the case when classical current lines lie in the mirror plane, relating N/S interfaces. The temperature dependences of the conductance and current-voltage characteristics of the normal parts of such symmetrical structures are identical to those in the *absence* of superconductors. The theory explains quantitatively our experimental results on the temperature and bias dependences of the differential resistance. It, thus, allows us to obtain the dependence of the value of the superconducting gap at the N/S interface $\Delta_{\rm eff}$, on the temperature and voltage bias.

We acknowledge Yu. Nazarov and A. Zaitsev for valuable discussions of the results. The Swedish Nanometer Laboratory and the Quantum Electron Kinetics Laboratory of the Russian Academy of Sciences were used to fabricate the samples. Financial support from the EPSRC (Grant Ref. No. GRL94611), the Russian HTS Programme (Project No. 96053), the Swedish TFR and NFR, the Wallenberg Foundation, and the Nanotechnology Initiative Fund of Royal Holloway College, University of London is acknowledged.

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