Evidence of two-electron tunneling interference in Nb/InAs junctions

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Abstract

The impact of junction transparency in driving phase-coherent charge transfer across diffusive semiconductor-superconductor junctions is demonstrated. We present conductivity data for a set of Nb-InAs junctions differing only in interface transparency. Our experimental findings are analyzed within the quasi-classical Green-function approach and unambiguously show the physical processes giving rise to the observed excess zero-bias conductivity.

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The lack of available states below the superconducting energy gap prevents single-electrons from being injected across normal metal-superconductor (NS) junctions at low bias. A two-electron tunneling process known as Andreev reflection [1], however, allows charge transfer across interfaces with non-zero transparency. The two electrons involved in this process upon entering the superconductor form a Cooper-pair and must therefore be linked by specific energy and phase relationships [2,3].

The detailed nature of the N region in proximity to the superconductor can have a significant impact on junction conductivity [4]. Indeed the interplay between phase-coherence in the N region and Andreev reflection can lead to enhanced or suppressed conductivity [5,6].Finite bias, temperature, and magnetic fields readily destroy phase coherence and consequently these phenomena are observed mostly around zero bias and at very low temperatures.

Experimentally, these coherent phenomena can be studied in the case of diffusive N electrodes. Beenakker [9] introduced the concept of reflectionless tunneling where the zero bias conductivity is predicted to present an unexpected linear dependence on interface transmission probability (analogous to a one-electron process). In the tunneling regime, Hekking and Nazarov [7,8] underlined the role of coherent phenomena in determining the constructive interference of the two electrons entering the superconductor. In the low transparency case, one can identify two regimes depending on the resistance of the disordered (phase coherent) region being larger or smaller than the barrier resistance. The excess conductivity around zero bias as a function of the latter increases or decreases, respectively. Unified theoretical descriptions of these transport phenomena are now available within the quasi-classical Green’s function [10] and the scattering matrix [3,11] approaches.

The first case (interface resistance limiting the conductivity) was invoked for a Cu-Al junction by Pothier et al. [12], the second (N-region resistivity dominant) for the superconductor-semiconductor junction results of Magnée et al. [13]. Identification of the specific regime was obtained by analyzing the relevant junction parameters. In this article we take advantage of the qualitatively different dependence of conductivity on junction trans-
parency to demonstrate two-electron tunneling interference in a set of InAs/Nb junctions. In our samples, in fact, zero-bias excess conductance develops for increasing the transparency of the junctions: as far as we know this is the first direct experimental demonstration of this characteristic trend. The data are quantitatively analyzed by solving the appropriate quasi-classical equations [10].

The samples consist of semiconductor-superconductor planar junctions, where the semiconductor part is a n-doped InAs (100) substrate with \( n = 1.3 \cdot 10^{18} \, \text{cm}^{-3} \). The superconductor part is Nb. The relevant semiconductor parameters are the resistivity \( \rho = 4 \cdot 10^{-4} \, \Omega \, \text{cm} \) and the mobility \( \mu = 1 \cdot 10^{4} \, \text{cm}^{2} \, \text{V}^{-1} \, \text{s}^{-1} \). InAs is one of the best choices for hybrid Sm-S devices, mostly owing to the lack of a Schottky barrier at the contact with a metal. Oxides and other impurities, however, give rise to a residual interface barrier region and several technological efforts have been made to improve the transparency of S-Sm junctions and maximize Andreev conversion [3,4,14]. In our case, junctions were fabricated after annealing substrates at a moderate temperature (340 °C) only marginally affecting the native oxide structure and its nonuniformities. This annealing procedure, however, minimizes the amount of water incorporated by the oxide and reduces the formation of Nb oxides [15]. The superconductor film (100-nm-thick Nb) was e-beam evaporated following substrate annealing and without breaking the vacuum. Substrate temperature during Nb deposition was kept at \( \approx 150 \, ^\circ \text{C} \) to promote adhesion of the superconducting film.

Circular junctions (75 \( \mu \text{m} \) diameter) were fabricated by standard photolithographic techniques and wet chemical etching in a \( \text{H}_{2}\text{O}:\text{H}_{2}\text{O}_{2}:\text{NaOH} \) solution. Back contacting was provided by metallizing the whole chip back. Samples were measured from 0.3 K to temperatures larger than the critical temperature \( T_{c} \approx 8.0 \, \text{K} \) of our Nb-on-InAs film and for static magnetic fields applied perpendicularly to the plane of the junctions using a \( ^{3}\text{He} \) closed-cycle cryostat equipped with a superconducting magnet.

Figure 1 shows the differential conductance \( G(V) \) of several contacts belonging to the same chip at \( T = 0.32 \, \text{K} \) with no applied magnetic field. The wide range of conductance values observed is linked to the above mentioned oxide inhomogeneity. Notably high con-
ductivity contacts exhibit zero-bias excess conductance. The latter effect was consistently more pronounced in more conductive junctions. As we shall argue in the following, more conductive junctions correspond to more transparent interfaces. The qualitative behavior of our junctions is therefore that studied by Hekking and Nazarov and excess conductance may be linked to the constructive interference of two-electron tunneling into the superconductor. This conclusion will be substantiated by the following quantitative analysis. High conductance curves are shown in a narrower range owing to heating effects at higher biases, but did exhibit a peak in proximity of \( V = \Delta/e \) (data not shown).

The experimental curves labeled (1) and (2) do not quite follow the expected behavior for a SN junction. The main discrepancies are in the detailed shape and in the position of the peaks at \( \Delta \). These deviations are related to the complex structure of the samples in the interface region. In order to describe electronic transport in our InAs/Nb junctions, we adopted the model first proposed in Ref. [15], namely we take into account the fact that the first layers of Nb are non-superconducting owing to the fabrication process (see Fig. 2). The potential drop still occurs at the metallurgical interface and therefore this interlayer region \((N_{Nb})\) can be considered at the same potential as the superconducting electrode. The thickness of \( N_{Nb} \) \((L)\) is expected to be of the order of a nm; nevertheless this interlayer strongly modifies the transport properties of the junctions. The various contributions to the current depend on the details of the sample close to the contact region and while the tunneling into the condensate (Andreev current) may not be very sensitive to the interlayer, the normal contribution strongly depends on the single-particle states available close to the interface [16].

The numerical evaluation of the current-voltage (I–V) characteristics is done in two steps. First we determine self-consistently the BCS gap in the Nb (close to the junction it will be suppressed due to proximity). Since we assume that there is no potential drop in this part of the structure we can use the equilibrium formalism. In the dirty limit, the quasiclassical retarded Green’s function \( \hat{g}^R(x,E) \) satisfies the Usadel equation [17].
\[ D \partial_x (\dot{g}^R \cdot \partial_x \dot{g}^R) + (iE + \Gamma_{in}(x)) \left[ \hat{\tau}_z + \hat{\Delta} \cdot \ddot{g}^R \right] = 0, \]  

(1)

with the constraints \( \dot{g}^R \dot{g}^R = 1 \) and \( \text{Tr} \dot{g}^R = 0 \). The hat refers to the Nambu notation (\( \hat{\tau}_z \) and \( \hat{\tau}_y \) are the Pauli pseudospin matrices). The Fermi energy is at \( E = 0 \). We assume that the inelastic scattering rate \( \Gamma_{in}(x) \) differs from zero only in the thin Nb interlayer close to the interface. The gap matrix \( \hat{\Delta}(x) = \Delta(x) \hat{\tau}_y \) is determined self-consistently by means of

\[ \Delta(x) = \frac{1}{2} \lambda(x) \int_0^{\omega_D} dE \text{Im}[g_{12}(x, E) \tanh(E/2T)], \]  

(2)

where \( \lambda(x) = \lambda \Theta(-x) \) (\( \lambda = \text{arcosh}(\omega_D/\Delta_{BCS}) \) is the BCS coupling constant, \( \Theta(x) \) is the Heaviside step function, \( \Delta_{BCS} \) is the BCS gap, \( \omega_D \) is the Debye cutoff frequency) and \( T \) is the temperature. The selfconsistent solution close to the interface enables us to determine the appropriate boundary condition for the determination of the I-V curves (along the lines of Volkov et al. [10])

\[ I = \frac{1}{e R_N} \int dE D(E) [f_0(E + eV/2) - f_0(E - eV/2)], \]  

(3)

where \( R_N \) the normal state resistance of the sample and \( f_0 \) the Fermi distribution function. The effective transmission coefficient of the structure

\[ D(E) = \frac{1 + r}{r M^{-1}(E) + \frac{1}{4} \int_0^d M_T^{-1}(x, E) dx} \]

with \( M(E) = \Re g_{11}^R(0^+) \Re g_{11}^R(0^-) + \Im g_{12}^R(0^+) \Im g_{12}^R(0^-) \) and \( M_T(x, E) = [\Re g_{11}^R(x, E)]^2 + [\Im g_{12}^R(x, E)]^2 \) is determined by the solution of the Usadel equation. The interface between the diffusive region and Nb is placed at \( x = 0 \) (\( x = 0^+/- \) indicated the normal/superconducting side of the interface). The result of this procedure leads to the fits shown in Fig. 3. The theoretical curves in Fig. 3 are obtained assuming the ratio \( r = R_T/R_D = 2.5 \) (where \( R_T \) and \( R_D \) are the interface and diffusive region contribution to the junction resistance, respectively). The fitting parameters in the \( N_{Nb} \) region are the length \( L \simeq 0.2 \xi_{Nb} \) (with \( \xi_{Nb} \) the experimental coherence length in the dirty S) and the inelastic scattering rate \( \Gamma_{in} = 0.4 \Delta_{BCS} \). All the curves of the set are fitted with the same parameters, and only the temperature is varied according to its experimental value.
Both $L$ and $\Gamma_m$ are consistent with the experimental expectations. From the measured value of $T_c$ it was possible to extract $\xi_{Nb} \simeq 8.0$ nm for our Nb-on-InAs film, obtaining in this way a value of the interlayer length $L \simeq 1.6$ nm consistent with the estimated thickness of the oxidized Nb interface region. The large value of $\Gamma_m$ is related to the fact that superconductivity is locally suppressed (we stress again that the rest of the Nb is ideal). The presence of the thin layer of "normal" Nb proved crucial to obtain a good quantitative agreement with the experimental data. In fact, at finite voltages the measured differential conductance is always larger than that predicted by a simple S-I-N system. This increased conductivity stems from the presence of the $N_{Nb}$ layer and the availability of states for the single-particle channel of the current. The latter are the subgap states of the proximized normal layer.

From the already given experimental parameters of InAs, we obtained a very good agreement between theory and experiments with $d = 200$ nm (which corresponds roughly to the estimated coherence length in the normal region) and a mean free path $l_e = 220$ nm at $T = 0.3$ K. The fitting parameter $r$ allows us to quantitatively show that for the junction corresponding to curve (1) the weight of the tunnel-barrier resistance is predominant with respect to the resistance of the diffusive region. A quantitative fit for curve (2) was also obtained (data not shown). As anticipated above this occurred for a lower value of the parameter $r$ ($r = 2$ compared to $r = 2.5$ for junction (1), reflecting the larger transparency of the interface in the corresponding contact). Although the various junctions are nominally identical, the native oxide nonuniformities can easily lead to the observed variations. The parameter values extracted from the fits show that our junctions are in an intermediate case as compared to the limit discussed in Ref. [7]. Though not deep in the asymptotic region, our analysis allows to extend the main qualitative features also to the range of parameters typical of the samples considered in this work.

The zero-bias conductance observed in the curves (3), (4), and (5) in Fig. 1 occurs on an increasing normal-state conductance value. The latter variation is influenced also by a concomitant variation of the junction effective area. For the present analysis,
however, we must focus on the increased zero-bias contribution which is dominated by the 
junction-transparency variation. This corresponds to the Hekking-Nazarov regime, in which 
increasing $\Gamma$ leads to a more pronounced conductance peak at $V, H = 0$. In terms of 
our parameters this means that $r$ lowers. In fact, this trend is also present in our model 
calculations: by lowering the barrier resistance the zero-bias excess conductance develops. 
For this set of curves, however, we were unable to obtain a quantitative agreement with the 
experimental data.

Further proof on the nature of the enhanced zero-bias conductivity can be gained ex-
perimentally by analyzing its temperature and magnetic field dependence. As mentioned 
above two-electron interference effects can be easily broken by voltage, temperature and 
magnetic field. Figure 4 shows the temperature and the magnetic-field (inset) dependence 
of the zero-bias conductance in junction (4). Cut-off values for temperature ($T \simeq 1.0$ K) 
and magnetic field ($B \simeq 6$ mT) are similar to those reported by other experimental groups 
for such effects [5]. Additionally we remark that at $T = 0.32$ K the width of the zero bias 
peak is of the order of $k_B T/e = 27 \mu$eV.

In conclusion, we have analyzed the influence of junction transparency on phase-coherent 
conductance in superconductor-semiconductor junctions. The dependence of the zero-bias 
excess conductance on interface transparency was directly observed and junction parameters 
estimated based on a quasi-classical Green’s function approach.

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FIGURES

FIG. 1. Experimental differential conductance vs voltage at $T = 0.32$ K and zero magnetic field for five Nb/InAs junctions belonging to the same chip. Numbers in parentheses label different junctions. The left and the right hand side insets show a magnification of data for junctions (3), (4), (5).

FIG. 2. Sketch of our one-dimensional model. S labels the pure Nb superconducting electrode, $N_{Nb}$ is a nonsuperconducting but strongly proxymized portion of Nb of thickness $L$ in equilibrium with S. The solid vertical line represents the tunneling barrier contributing with $R_T$ to the junction resistance. $N_D$ is the nonequilibrium portion of InAs of length $d$ and resistance $R_D$. N labels the InAs electrode.

FIG. 3. Normalized differential conductance vs voltage with no applied magnetic field at three different temperatures $T = 0.32, 1.2, 3.0$ K. Data refer to contact labeled (1) in Fig. 1. $R_N$ is the normal-state resistance. Experimental: open triangles, theoretical: solid lines. Parameters are $L = 1.6$ nm, $d = 200$ nm, $\Delta_{BCS} = 1.265$ meV, $\Gamma_{in} = 0.4 \Delta_{BCS}$, $r = 2.5$. All experimental curves are fitted with the same parameters, only the temperature is varied according to its experimental value.

FIG. 4. Temperature dependence of the zero-bias conductance relative to contact labeled (4) in Fig. 1. The inset shows the magnetic-field dependence for the same contact at $T = 0.32$ K. Magnetic field was applied perpendicularly to the junction plane.
\( \frac{dI}{dV} \) (\( \Omega^{-1} \))

V (mV)

\( -0.3 \) 0.0 0.3

\( 9.7 \) 9.8
$T = 3.00\text{ K}$

$T = 1.20\text{ K}$

$T = 0.32\text{ K}$
\[ \left( \frac{dI}{dV} \right)_{V=0} (\Omega^{-1}) \]

- **H = 0**

- **T = 0.32 K**

![Graph showing data points for (dI/dV)|_{V=0} vs. T (K) and H (mT)](image)