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Phase Conjugated Andreev Backscattering in Two-Dimensional Ballistic Cavities

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We have experimentally investigated transport in two-dimensional *ballistic* cavities connected to a point contact and to two superconducting electrodes with a tunable macroscopic phase difference. The point contact resistance oscillates as a function of the phase difference in a way which reflects the ballistic nature of the transport in the cavity. We interpret our results in terms of a semiclassical model that relies on the properties of the phase conjugated trajectories on which a hole traces the path of the electron back to the emitting point contact. This model provides quantitative predictions (with no fitting parameters) as well as a clear physical picture. [S0031-9007(97)02743-9]

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Andreev reflection (AR) [1] is a fundamental process that converts an electron incident on a superconductor into a hole, while a Cooper pair is added to the superconducting condensate. Because of conservation of momentum, the hole is reflected back in the direction of the incoming electron. This phenomenon, known as retroreflection, is the most striking feature of AR at the classical level. In metals the presence of retroreflection has been well established in point contact (PC) spectroscopy on ballistic normal (N)/superconductor (S) bilayers [2]. In these experiments the N/S interface is smooth on the scale of the electronic Fermi wavelength λ_F .

In the past few years, experiments [3,4] and theory [5] have focused on quantum aspects of AR. In this context, the most relevant property of AR is the phase conjugation of the electron-hole wave at the Fermi energy, i.e., the possibility for the hole partial waves to trace back the electron ones, canceling the phase shifts due to the orbital motion and producing a large constructive interference. As a consequence of this phase conjugation, an Andreev reflected hole has the tendency to return to the point where the incoming electron started from, even when such an effect cannot be expected from classical mechanics [5].

In this paper we investigate experimentally, for the first time, transport in a two-dimensional ballistic cavity connected to a PC on one side and to two superconducting electrodes on the opposite side (Fig. 1). We have studied the quantum properties of AR, by analyzing the oscillations of the PC resistance as a function of the tunable macroscopic phase difference of the superconducting electrodes. The oscillations are described remarkably well by a simple model that takes into account the properties of ballistic phase conjugated electron-hole trajectories. The contribution of these trajectories survives in spite of the absence of classical retroreflection (due to disorder at the superconductor interface).

Figure 1 is a scanning electron microscopy (SEM) micrograph of one of the samples. The structure consists of a constriction (PC) in a InAs/AlSb quantum well (which hosts a two-dimensional electron gas (2DEG) confined to the InAs layer; electron density $N_s = 1.75 \times 10^{16} \text{ m}^{-2}$, $\lambda_F = 21 \text{ nm}$, elastic mean free path $l_e = 1.9 \text{ }\mu\text{m}$) leading to a cavity connected to two superconducting (Nb) terminals, as shown in Fig. 1 (we have also studied structures with two PC's [inset Fig. 2(b)]). The superconducting terminals are the ends of an open superconducting loop (enclosed area $\approx 6 \text{ }\mu\text{m}^2$). The cavity is rectangular ($\approx 1.6 \times 0.6 \text{ }\mu\text{m}^2$); the separation between the superconducting electrodes is $\approx 0.2 \text{ }\mu\text{m}$ and the width of the PC, determined from SEM inspection, is $\approx 150 \text{ nm}$.

The structures are made by means of a two step electron beam lithography process. In the first step we define the profile of the cavity and the PC using a wet etching technique to remove the top AlSb as well as the InAs layer. In the second step a pattern for the superconducting ring is defined. After removing the AlSb top layer in this region (again by wet etching) the sample is loaded into an *e*-beam evaporator and, prior to the Nb deposition, the exposed InAs is cleaned by Ar ion milling [6] to improve

FIG. 1. Left: one of the single PC samples. The dark region is the etched insulating trench. It defines a constriction (PC), connected to the rectangular cavity, bounded on top by two superconducting electrodes. Right: phase conjugated trajectories representing the three different sets (see text).

FIG. 2. Magnetoresistance of the structure with one (a) and two (b) PC's. The insets illustrate the contact configuration. The lower curves are the negative B measurements, plotted on the positive axis for convenience. In (b) the arrow points to the focusing peak.

the transparency of the 2DEG/S interface. Lift off of the 45 nm evaporated Nb ($T_c \approx 6.5$ K, superconducting gap $\Delta \approx 1$ mV) layer concludes the processing.

The high quality of the 2DEG in the PC's and the cavity region is preserved since the InAs is still covered by the AlSb top layer. Hence, we expect that transport occurs in the ballistic regime (l_e larger than the sample dimension). This is the main difference between our samples and the interferometers previously realized using InAs 2DEG's or metal films [3,4].

To establish the ballistic nature of the transport in the samples, we first investigate their magnetoresistance. In Fig. 2(a) the magnetoresistance of a sample with a single PC is shown. For positive field the PC resistance is roughly constant up to $B \approx 2$ T and then increases due to magnetic depopulation of subbands [7]. This result is expected for a steep confining potential, such as the one provided by the Fermi energy pinning at the edges of the InAs. From the slope $\Delta R/\Delta B$ at high field we calculate the electron density in the channel, $1.4 \times 10^{16} \text{ m}^{-2}$, slightly lower than in the wider regions. For negative field the magnetoresistance also behaves according to the theory of transport in ballistic constrictions [8].

From the magnetoresistance data we can extract the effective width of the PC [8] to be ≈ 130 – 140 nm depending on the sample (comparable to those obtained from SEM inspection). The resulting Sharvin resistances are 980 to 1080 Ω , and are within 10% of the measured values. This implies that scattering from the edges is

predominantly specular, as also indicated by the low field magnetoresistance [9].

Figure 2(b) shows a measurement on one of the samples with two PC's. Current is injected into one of the PC's and voltage is measured with the other [inset Fig. 2(b)]. The observation of flat Hall plateaus indicates the high quality of the material. At $B \approx 0.45$ T, when the cyclotron diameter is equal to the distance between the two PC's, we observe a pronounced structure in the $R(B)$ curve, corresponding to the first magnetic focusing peak [10]. Part of the electrons have to pass underneath one of the superconductors (where the 2DEG is disordered after the Ar ion milling [6]) which explains why the peak is broad and smeared. Higher order peaks are not observed, probably because the edge of the cavity in between the two PC's is not straight enough. For negative B the injected electrons are deflected away from the second PC and the measured resistance decreases. The vanishing of the resistance for $B \geq 0.9$ T confirms that transport occurs in the ballistic regime, since the presence of impurities would scatter electrons into the second PC, leading to a finite resistance value.

We now proceed to study the effects of the superconducting terminals. We discuss in detail the behavior of the three samples with a single PC. Measurements of the PC differential resistance as a function of the dc voltage show a dip at energies below Δ , due to AR resulting from a high interface transparency. In all the samples the dip magnitude is only ≈ 50 Ω , much smaller than the ≈ 500 Ω classically expected [2]. We attribute the absence of the classical effect to the disorder present at the 2DEG/S interface. The disorder is induced by the Ar ion milling, that reduces the elastic mean free path in the region under the superconductor to ≈ 40 nm, comparable to λ_F [6]. As a consequence, holes can be reflected in all possible directions [11]. This conclusion is supported by the absence of any indication of magnetic defocusing [2]. In the present geometry this should manifest itself as a resistance increase for B increasing from 0 to ≈ 0.1 T, which is not observed in Fig. 2(a).

Figure 3 shows the dependence of the PC resistance on a low magnetic field, measured in a dilution refrigerator, at a temperature $T \approx 50$ mK, using a standard lock-in technique in a four probe configuration (two probes are connected to the Nb ring and two to the PC). The change in phase difference $\Delta\phi$ induced by the magnetic flux Φ piercing the area defined by the superconducting loop ($\Delta\phi = 2\pi\Phi/\Phi_0$, $\Phi_0 = h/2e$) produces the resistance oscillations (Fig. 3). Their amplitude decreases with increasing applied magnetic field from 0 to 150 G [12] (the effective magnetic field present in the cavity is approximately 30% higher due to the Meissner effect in the adjacent superconducting electrodes). This behavior has been observed in all of the samples.

A number of remarkable features can be recognized in the oscillations. One is the large magnetic flux required for their suppression, $5h/e$ through the cavity,

FIG. 3. (a) Resistance oscillations measured at $V_{dc} = 0$ (trace 2) and $V_{dc} = 0.8$ mV (trace 3, offset for clarity) as a function of the applied field (the actual field in the cavity is ≈ 1.3 times larger, due to the Meissner effect in the adjacent Nb electrodes). Trace 1 is a theoretical curve obtained from Eq. (1) at $E = 0$. The amplitude and the offset of trace 1 have been adjusted to facilitate the comparison with trace 2; the difference between the applied field and that actually present in the cavity has been taken into account. (b) Fourier transform of the measured trace 2 in (a) (solid line) and the theoretical curve (dotted line, offset for clarity).

five times larger than the one reported in Ref. [4] for samples in the diffusive regime. A second feature is a regular beating pattern modulating the amplitude of the oscillations [Fig. 3(a)], never reported in experiments on diffusive interferometers. The position of the beating nodes is energy dependent [compare traces 2 and 3 in Fig. 3(a)]. The Fourier spectrum is also remarkable. The central peak is split (corresponding to the observed beating pattern). Lobes are present at its sides [Fig. 3(b)]. The side lobes continue to persist at all the energies at which the oscillations are observed. Contrary to the other features, the shape of these lobes is sample dependent, and can be less pronounced than the one shown here.

In the rest of the paper we discuss a semiclassical model which relates the features observed in the oscillations to the properties of phase conjugated trajectories. The model describes the following physical picture. Since λ_F is not very much smaller than the PC width, “diffraction” of part of the electrons injected into the cavity cannot be neglected in the description of the observed oscillations [13]. The diffracted electrons have a quantum mechanical amplitude to be transmitted through the PC in any possible direction. The probability for a diffracted electron to produce a hole returning to the PC is

the squared sum of the (complex) amplitudes of all the possible processes. At a semiclassical level these processes are described in terms of electron-hole trajectories. Their amplitudes are obtained by calculating the phase that the electron and the hole accumulate on their path.

For each partial electron wave leaving the PC and propagating ballistically to the superconductor, there exists a hole partial wave which traces the electron trajectory back to the PC. In a first order approximation, namely, if we only consider processes involving a single reflection from the superconductor, these are the phase conjugated trajectories which contribute to the macroscopic phase induced modulation of the AR probability R_{he} at the PC. Since R_{he} enters the expression for the conductance [14] linearly, this modulation produces the observed resistance oscillations. In the approximation just mentioned the expression for R_{he} reads

$$R_{he}(E) = K \left| \int_{-\theta_0}^{\theta_0} d\theta \cos \theta e^{i \left\{ \int [\vec{k}_e(E) - \vec{k}_h(E)] \cdot \vec{dl} + 2e/h \int \vec{A}(\vec{r}) \cdot \vec{dl} + \phi_i \right\}} \right|^2. \quad (1)$$

Here θ is the angle of emission of the electrons with respect to the direction normal to the PC [15]. Integrating over this angle corresponds to summing the amplitude of all the processes that contribute to R_{he} in the present approximation [16]. $\vec{k}_e(E)$ ($\vec{k}_h(E)$) is the electron (hole) [14] wave vector, A is the vector potential describing the magnetic field in the cavity, and ϕ_i ($i = 1, 2$; Fig. 1) is the macroscopic phase of the superconductors, which is picked up by the holes upon AR.

We have assumed that electrons are emitted with a cosine distribution, and θ_0 is chosen so that all those trajectories in which an electron hits the side walls of the cavity, at most once, are taken into account (this includes the largest part of the emission angle since θ_0 is $\approx 80^\circ$). The integration over θ is performed numerically, by separating the integration domain in three parts, corresponding to different sets of trajectories (Fig. 1): (a) those that do not touch the side walls of the cavity, (b) those that hit the left (right) superconducting electrode after a reflection on the left (right) side of the cavity, (c) those that hit the right (left) superconducting electrode after a reflection on the left (right) side of the cavity.

Finally, K is a constant which depends on the AR probability at the 2DEG/S interface and on the specific coupling between the PC and the cavity [17]. Since this coupling cannot be realistically modeled, Eq. (1) does not predict the absolute magnitude of the oscillations.

The results obtained from Eq. (1) are compared with the measurements in Fig. 3. No free parameters have been introduced, and all the geometrical dimensions have been obtained from a SEM micrograph. The model reproduces quantitatively the position of the beatings (that results to be energy dependent theoretically, as well as experimentally) [18] and the shape of the features in the Fourier transform,

such as the width of the central peak and its splitting. The side lobes are present in the computed Fourier spectrum even though they do not compare as nicely with the data. Nevertheless the model gives a possible explanation of the behavior of these lobes. From our calculations we find that they are due to the trajectories belonging to group (c) (Fig. 1). These trajectories are those in which electrons are emitted at a large angle with respect to the direction normal to the PC. Their contribution to R_{he} depends strongly on the emission distribution from the PC. In Eq. (1) a cosine has been chosen, whereas in real devices the distribution depends on the details of the sample. For instance, the Fourier transform of the resistance oscillations measured on the sample shown in Fig. 1 exhibits lobes much less pronounced than those of Fig. 3(b). This might be expected, since the shape of this PC suggests that the electrons are partially collimated in the forward direction [19].

The model also describes the energy dependence of the oscillation amplitude (normalized to that at $E = 0$). Equation (1) accounts for the contribution to R_{he} of single AR processes and predicts a monotonous decrease of the amplitude with increasing energy, induced by the dephasing due to the term $e^{i \int [\tilde{k}_e(E) - k_h(E)] d\tilde{l}}$. Higher order processes, i.e., electron-hole conversions involving more than one AR, can modify this conclusion. For instance, since at $E = 0$ a phase $e^{i\pi/2}$ is picked up upon AR [17], electrons converted into holes after three AR (second order processes) interfere destructively with those converted into holes via a single AR, thus decreasing the oscillation amplitude. However, due to the larger length of their phase conjugated trajectories, dephasing suppresses the contribution of high order processes at low energy: For processes involving three AR, suppression occurs at an energy E_0 such that $[k_e(E_0) - k_h(E_0)]6L \approx 2\pi$ (L linear dimension of the cavity). Consequently, the amplitude of the oscillation increases with increasing energy as long as $E < E_0$, and decreases when $E > E_0$, a behavior similar to that shown by diffusive samples [5], apart from the energy scale E_0 , now only determined by the size of the system.

We have carefully measured the energy dependence of the oscillation amplitude in two samples [20]. The first exhibits a monotonous amplitude decrease with increasing E , in quantitative agreement with the predictions of Eq. (1). In the second sample the oscillation amplitude increases ($\approx 10\%$) with increasing E from 0 to 0.25 mV, before eventually decaying for $E > 0.25$ mV, indicating that a correction due to higher order processes is observable. Given the typical linear dimension of the cavity (1 μm), the energy 0.25 mV agrees with the above estimate for E_0 .

Finally, the importance of the phase conjugated trajectories is confirmed by the measurements on the structures with two PC's. There we can compare the oscillations measured in the two terminal (current and voltage probes

connected to the same PC) with those measured in the three terminal (current and voltage probes connected to different PC's) configuration, where phase conjugated trajectories cannot play any role. As expected, in the latter case the oscillations ($\approx 1 \Omega$, 30 times smaller than in the two terminal configuration) are dominated by sample specific behavior for all values of B , even at $B = 0$.

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