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Electron transport in multi-terminal 2DEG-superconductor devices

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We have studied multi-terminal transport in normal-superconductor devices. We will describe the transport in terms of an extended Landauer-Büttiker transport formalism, which will be illustrated by an experimental test of the reciprocity relations. Furthermore, we have found a negative three-terminal resistance and non-local resistance modulations.

1. INTRODUCTION

A normal-superconducting (NS) interface has an interesting property for studying mesoscopic transport. The macroscopic phase of the superconductor is transferred to phase of the Andreev reflected particle in the normal conductor. In a SNS-device the Andreev reflected hole (or electron) waves can interfere leading to a component in the conductance, which is periodically modulated by the superconducting phase difference $\Delta\varphi$. Multi-terminal transport in normal mesoscopic devices is presently well understood in terms of the Landauer-Büttiker transport formalism [1] in contrast to transport in diffusive mesoscopic NS-devices [3].

We have designed a multi-terminal SNS-device by coupling an interrupted superconducting loop to a cross-shaped 2 dimensional electron gas (2DEG) and found that transport can be described by an extended Landauer-Büttiker transport formalism, taking into account phase-coherent Andreev reflection.

The multi-terminal interferometer as shown in Fig. 1 is fabricated in a similar way as described in [5]. We used an InAs/AlSb heterostructure, because of the absence of a Schottky barrier between the superconductors (Nb) and the 2DEG in the 15nm InAs layer underneath ($l_e \simeq 0.2\mu\text{m}$ and $n_s \simeq 1.5 \cdot 10^{16}\text{m}^{-2}$). Insulating trenches in the InAs layer were defined by means of wet chemical etching. The phase difference $\Delta\varphi$ between the Nb terminals changes linearly with the applied magnetic flux Φ through the Nb loop: $\Delta\varphi = 2\pi\Phi/\Phi_0$ with $\Phi_0 = h/2e$. Note that Φ also penetrates the normal cross-shaped 2DEG itself.

Figure 1: Sample layout. The left-hand panel shows a schematic picture of the cross-shaped 2DEG with the superconducting terminals. The contacts (1), (2), (3) and (4) are connected to the cross-shaped 2DEG and contacts (0) are connected to the superconducting Nb loop. The length of the InAs channel between the Nb terminals (0) is about $0.9\mu\text{m}$ and its width is $0.25\mu\text{m}$. The right-hand panel shows a SEM micrograph.

2. RESULTS

2.1. Reciprocity relation

The Landauer-Büttikers transport formalism [1] is based on the fact that all microscopic scattering processes can be condensed in a transmission and reflection amplitudes between perfect leads, which is sensitive to the magnetic flux and the superconducting phase. Furthermore, the conductance can be expressed in terms of transmission and reflection probabilities. Time-reversal symmetry imposes the following reciprocity relation [1, 2]:

$$\mathcal{R}_{ij,kl}(\Phi, \Delta\varphi) = \mathcal{R}_{kl,ij}(-\Phi, -\Delta\varphi), \quad (1)$$

Figure 2: Panel (a) and (b) display respectively the "2-terminal" magnetoresistance $R_{30,40}$ and $R_{10,20}$ measured at $T=50\text{mK}$. Panel (c) and (d) show respectively the 3-terminal magnetoresistance $R_{30,10}$ and $R_{10,30}$.

where ij and kl represent current or voltage probes.

In Fig. 2 we have plotted the 2 and 3-terminal magnetoresistance. The resistance is periodically modulated with a period of 1.5 Gauss. In ref. [5], we have shown that around zero magnetic field (± 100 Gauss) the resistance modulation is mainly non-sample specific (ensemble averaged) [4], but for higher magnetic fields sample-specific conductance fluctuations modulated by $\Delta\varphi$ are responsible for the resistance modulation. Apart from minor deviations, we can see that the "2-terminal" resistances $R_{30,40}$ and $R_{10,20}$ (panel (a) and (b)) are symmetric in Φ and $\Delta\varphi$. Note that the two Nb terminals have the same electrochemical potential and thus act as one reservoir. The 3-terminal resistance $R_{30,10}$ (panel (c)) shows an asymmetry in Φ and $\Delta\varphi$, which is reversed when the current and voltage probes are interchanged ($R_{10,30}$, panel (d)). These observations are in agreement with the extended Landauer-Büttiker transport formalism.

2.2. Negative 3-terminal resistance

A 3-terminal resistance of a normal conductor always measures a positive value, since the electrochemical potential of the voltage probe is bounded by the source and drain potential. Looking at Fig. 3 (a), we can see that at a certain magnetic field (-780 Gauss) the 3-terminal resistance went negative. The explanation for this phenomenon is quite simple. In

Figure 3: Panel (a) displays the 3-terminal magnetoresistance $R_{30,20}$ at $T=50\text{mK}$ of a device with an increased overall resistance ($R_{30,40} \sim 10\text{k}\Omega$). Around -780 Gauss the resistance is negative. Panel (b) shows the non-local resistance $R_{30,12}$.

the presence of a superconductor also Andreev transmission (e.g. from electron to hole) occurs. When Andreev transmission exceeds the normal transmission into the voltage probe, a negative electrochemical potential is built up.

2.3. Non-local resistance modulations

One of the most striking features of phase-coherent transport is its non-locality. The resistance measured in a multi-terminal configuration can be affected by a change in quantum interference in parts of the conductor where no net current flows. In our device the resistance $R_{30,12}$ was modulated (see Fig. 3 (b)), although no net current was flowing in the arm of the cross connected to the voltage probes. This clearly demonstrates that the phase-coherence length extends into the separate leads connected to the cross.

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