Mesoscopic transport in hybrid normal-superconductor nanostructures

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Mesoscopic physics concerns with the properties of small systems with sizes in the range of a few nanometers to micrometers at low temperatures, typically below 1 K. The constant progress in nano-fabrication techniques allows for a controlled realization of these structures and a consequent increasing interest in this physics.

Characteristic of superconductivity is the macroscopic phase coherence of the order parameter and the supercurrent flow. On the one hand, superconductivity adds new degrees of freedom and makes the physics of mesoscopic systems richer. This is the case of hybrid normal (metallic or semiconducting)-superconductor (NS) structures. On the other hand, superconducting properties are deeply influenced by mesoscopic effects.

Our efforts in this field are both on the experimental and theoretical sides, and comprise many different aspects. They range from the fabrication and characterization of ballistic Josephson junctions, to the exploitation of out-of-equilibrium transport in order to realize transistors and electron coolers, from the study of adiabatic pumping to the production and detection of entangled pairs of electrons. In the following we shall briefly describe all these topics.

The electric transport through NS systems is dominated by the conversion of normal current into supercurrent (a process called *Andreev reflection* [1]), which takes place at the interface. In ballistic structures comprising two superconducting electrodes coupled by a semiconducting (Sm) region, coherent sequential Andreev cycles establishing between the superconductors may lead to a set of resonant levels (Andreev bound states), whose energies are dependent on the difference of the macroscopic phases of the two superconductors. These bound states are responsible for carrying the Josephson current flow through the whole junction. The probability of Andreev reflection largely determines and affects the electron transport properties of S-Sm-S weak-links. It is, indeed, by now well established that the crucial issues to be addressed in order to improve the performance of these devices include S-Sm interfaces with high transmissivity (as required for an efficient Andreev reflection). To this end, an efficient method is based on the exploitation of III-V semiconductor alloys with high In content and in particular on InAs-based 2DEGs. These can provide Schottky barrier-free metal-semiconductor contacts.

We have fabricated and characterized highly transmissive Nb/2DEG/Nb ballistic junctions made in the InAs/AlSb system (Fig. 1) [2]. Current-voltage characteristics were measured down to 0.4 K (Fig. 2) and the observed supercurrent behavior was analyzed within a ballistic model in the clean limit.

This investigation allows us to demonstrate an intrinsic interface transmissivity exceeding 86% in our system. The reproducibility of the fabrication protocol makes it of interest for the experimental study of InAs-based S-Sm hybrid devices.

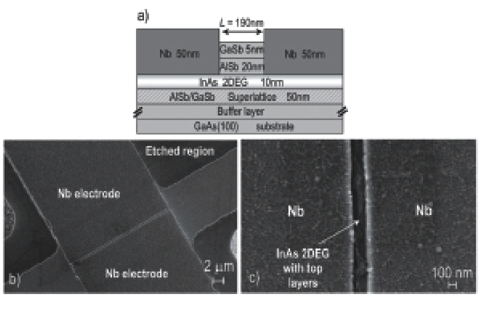


Fig. 1

Fig. 1
(a) Sketch of the Nb/InAs-2DEG/Nb microstructure. The Nb-electrode separation is 190 nm.
(b) Scanning electron micrograph of the device.
(c) Magnified view of figure (b) showing the semiconductor channel separating the two Nb contacts.

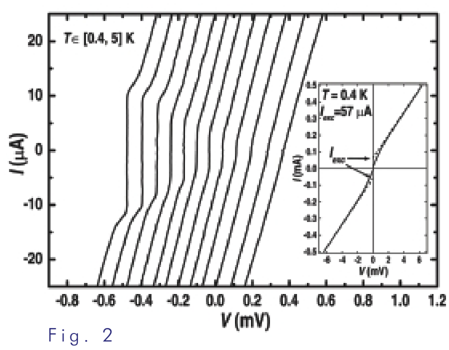


Fig. 2

Fig. 2
Current-voltage characteristics of the Nb/InAs/Nb weak link for different temperatures. Curves are horizontally offset for clarity. The inset shows the current-voltage characteristic measured at T = 0.4 K over a wider bias range. The linear extrapolation to V = 0 yields an excess current of 57 mA.

Nonequilibrium effects in mesoscopic superconducting circuits have been receiving a rekindled attention during the last few years [3]. The art of controlling Josephson coupling in SNS weak links is at present in the spotlight: a recent breakthrough in mesoscopic superconductivity is represented by the SNS transistor, where supercurrent suppression as well as its sign reversal (p-transition) were demonstrated [4]. This was achieved by driving the quasiparticle distribution in the weak link far from equilibrium [5] through external voltage terminals. We have demonstrated that it is possible to tailor the quasiparticle distribution through superconductivity-induced nonequilibrium in order to implement a unique class of superconducting transistors [6]. This can be achieved when mesoscopic control lines are connected to superconducting reservoirs through tunnel barriers (I), realizing a SINIS channel (see Fig. 3). The peculiar quasiparticle distribution in the N region, originating from biasing the S terminals, allows one to access several regimes, from supercurrent enhancement with respect to equilibrium to a large amplitude of the p-transition passing through a steep supercurrent suppression (see Fig. 4). These features are accompanied by a large current gain (up to some 10^5 in the region of larger input impedance) and reduced dissipation. The ultimate operating frequencies available open the way to the exploitation of this scheme for the implementation of ultrafast cryogenic current and/or power amplifiers. From the experimental side, we have fabricated a SNS mesoscopic Josephson junction in which the critical current is tuned through normal current injection using a symmetric electron cooler [7] directly connected to the weak link [8] (see Fig. 5). We have achieved both enhancement of the critical current by more than a factor of two, and supercurrent suppression by varying the cooler bias (Fig. 6). Furthermore, this transistor-like device had demonstrated large current gain (~20) and low power dissipation [7].

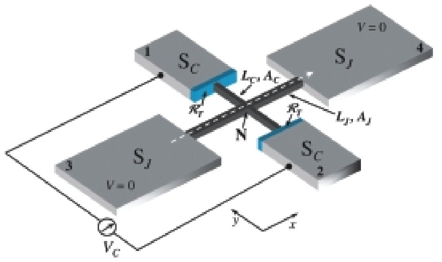


Fig. 3
Scheme of the Josephson transistor. The supercurrent (along the white dashed line) is tuned by applying a bias voltage V_C across the SINIS symmetric line connected to the center of the weak link. The superconducting gaps D_J and D_C are, in general, different and all N wires are assumed quasi-one-dimensional.

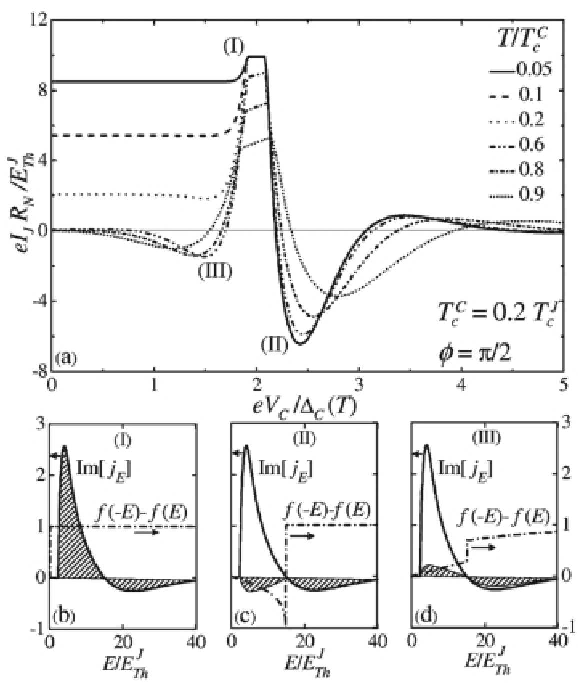


Fig. 4
(a) Supercurrent vs control voltage V_C at different temperatures. Bias regions labelled (I), (II) and (III) indicate supercurrent enhancement due to quasiparticle cooling, high-voltage p-state and low-voltage p-state in the high-temperature regime, respectively.
These are qualitatively explained in (b), (c) and (d) where hatched areas represent the contribution to supercurrent arising in such bias ranges.

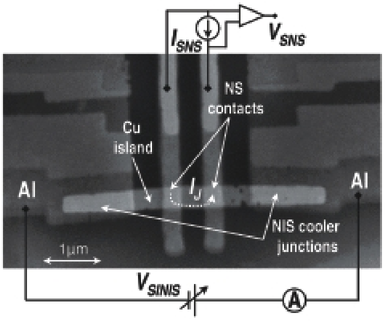


Fig. 5

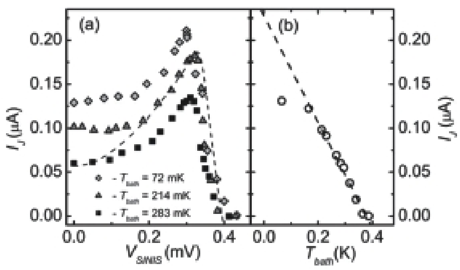


Fig. 6

Fig. 5
Scanning electron micrograph of a typical structure including a sketch of the measurement circuit. Two superconducting Al electrodes are connected through insulating barriers to a Cu island so to realize a symmatric SINIS electron cooler. The supercurrent I_J in the Al/Cu/Al junction is tuned upon voltage biasing the SINIS control line.

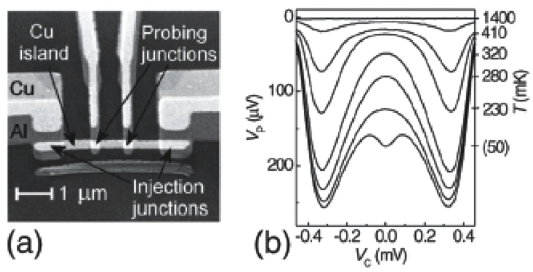
Fig. 6
(a) Critical current I_J vs control voltage V_{SINIS} at three different bath temperatures. (b) Equilibrium supercurrent (V_{SINIS} = 0) vs bath temperature. Dashed line in (a) represents the theoretical behavior assuming a linear approximation of I_J (T_{bath}) shown in (b).

To assign a temperature to a system one needs to assume that the energy relaxation within the system is faster than any rate associated with the heat flux between the system in concern and its surroundings. If this condition fails, the energy distribution of the particles of which the system is formed is non-thermal, and applying the concept of temperature is, strictly speaking, inappropriate. Such a limit can be achieved in submicron-size electron *coolers* at low temperatures. We demonstrate both theoretically and experimentally [9] two limiting factors in cooling electrons using biased NS tunnel junctions to extract heat from a N region into a superconductor (Fig. 7). First when the injection rate of electrons exceeds the internal relaxation rate in the metal to be cooled, the electrons do not obey to the Fermi-Dirac distribution and the concept of temperature can not be applied as such. Second, at low bath temperature, states within the superconducting gap induce anomalous heating and yield a theoretical limit of the achievable minimum temperature.

A particle current can be obtained, even in absence of a transport voltage, by a pumping mechanism, i.e., by varying in time some properties of a mesoscopic conductor. If the time scale for the variation of the scattering matrix describing the conductor is larger than the transport time, then the pumping is *adiabatic* and the number of particles transferred per period does not depend on the detailed time evolution of the scattering matrix but only on geometrical properties of the pumping cycle [10].

Within the scattering approach, we have developed a model for adiabatic quantum pumping in hybrid NS systems where several superconducting leads are present [11]. This is exploited to study Andreev-interference effects on adiabatically pumped charge in a 3-arm beam splitter attached to one normal and two superconducting leads with different phases of the order parameters (see Fig. 8). We have derived expressions for the pumped charge through the normal lead for different parameters of the scattering region, and elucidated the effects due to Andreev interference. In contrast to what happens for voltage-driven transport, Andreev interference does not yield in general a pumped current which is a symmetric function of the superconducting-phase difference.

Fig. 7
Scanning electron micrograph of a typical cooler sample made of Al/Cu (a) and electron temperature vs control voltage V_C at different bath temperatures (b). The probing junctions in (a) are used to measure the electron temperature as well as to extract the out-of-equilibrium quasiparticle distribution functions.



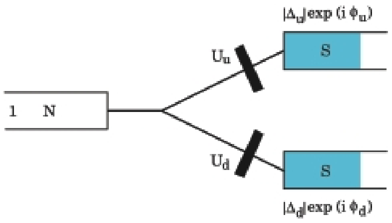


Fig. 8

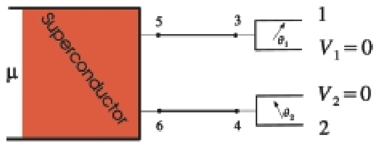


Fig. 9

Fig. 8
Schematic picture of the Andreev interferometer, consisting of a symmetric beam splitter with tunnel barriers added on the two arms where the superconducting leads are connected.
The strength of the barriers can be varied in time and are used as pumping fields. Experimentally, the system could be fabricated in a Sm/S hybrid structure and the additional time-varying barriers could be realized by applying time-dependent voltages to external gates.

Fig. 9
Setup of a superconducting beam splitter (colored region) for testing the CH inequality. Bold lines represent two conductors. The superconducting condensate electrochemical potential is set to, while terminals 1 and 2 are grounded.

Recently attention has been devoted to the manipulation of entangled states in a solid state environment. This interest is motivated by the idea to realize a solid state quantum computer, and by now several works discuss how to generate, manipulate and detect entangled states in solid state systems. In many proposals superconductivity has been identified as a possibility for the creation of entangled pairs of electrons. The idea is to extract the two electrons which compose a Cooper pair (a pair of spin-entangled electrons) from two spatially separated terminals. Since Bell's work [12], it is known that a classical theory formulated in terms of a hidden variables satisfying reasonable condition of locality, yields predictions which are different from those of quantum mechanics. These predictions were casted into the form of inequalities which any realistic local theory must obey. We have derived a Bell inequality for the full electron counting statistics and discuss its properties [13]. The formulation we follow is based on what is known as the Clauser-Horne (CH) inequality [14]. We have analyzed the case of a superconducting beam splitter depicted in Fig. 9, demonstrating the full violation of the CH inequality (Fig. 10), and therefore the presence of entanglement.

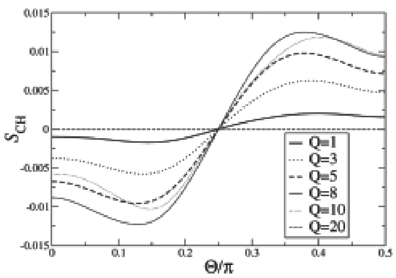


Fig. 10
Violation of the CH inequality (S_{CH}>0) occurs for detector angles 2 Q= q_1-q_2 larger than p/2 for all values of detected electron pairs Q.

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