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Pumping energy and charge by hybrid tunnel junctions

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Abstract
Following the outline of my talk at LT25 I give a brief review of hybrid tunnel junctions as electronic refrigerators and as single-electron sources.

In some applications local refrigeration can be beneficial: an electronic cooler where cooling is achieved by simply pushing an electric current through the device can then be an ideal solution. A hybrid tunnel junction, where one of the two conductors is made of a material with a gap in its density of states, can be employed in electronic cooling. For instance, a superconductor (S) with the BCS gap, facing a normal metal (N) through a tunnel barrier (I, insulator), is ideal for practical on-chip refrigeration of N at cryogenic temperatures. The first experimental demonstration of the effect was put forward by Nahum *et al* in 1994 [1]. An efficient electronic refrigerator, in the form of a double junction SINIS device, was demonstrated soon after by Leivo *et al* [2]: in the latter device electrons could be cooled from 300 mK down to about 100 mK temperature in an aluminium (S)–copper (N)-based configuration. It was soon noticed that the technique is not limited to cooling only electrons: the lattice refrigeration was demonstrated by Manninen *et al* [3], and a dielectric platform was subsequently refrigerated from 200 to 100 mK using a number of SINIS electron coolers in parallel [4]. Electronic cooling in an SIS'IS system of two different superconductors (Al and Ti) was soon demonstrated as well [5]. This interesting system was recently revisited [6]. Theoretically, the cooling power of the device is infinite at the biasing point where the edges of the two superconducting gaps meet [7]. In practice this leads to large but naturally finite cooling power: the singularities in the density of states of real superconductors are smeared because of, for example, pair breaking. In the experiments, the lower T_C superconductor (Ti) could be refrigerated by this method from its normal state deep into the superconducting phase. Another interesting system where electronic cooling was demonstrated is a superconductor facing a degenerate semiconductor with a Schottky barrier as an 'insulator' I [11].

The initial attempts to increase the cooling power of the junctions were not extremely successful, but useful results on, for example, the generation and relaxation of non-equilibrium quasiparticles were obtained [8–10]. Later on, a significant step forward in increasing the cooling power was achieved by Clark *et al* [12] using an inverted fabrication method and different materials. This new process lead to the development of a refrigerator of a 'macroscopic' semiconductor detector using several SINIS junctions [13], see also [14]. More recently a refrigerator of an x-ray transition edge sensor was realized using this technique [15].

During the past few years the studies of electronic refrigeration have focused on the limitations of the process set, for example, by Andreev reflection [16], or on the quest for improved tunnel barriers [17]. In our group at the Helsinki University of Technology, together with collaborators from SNS Pisa and CNRS Grenoble, we have investigated the interplay of Coulomb blockade and electronic refrigeration. We have proposed an electronic RF refrigerator, where a normal conductor in the form of an island of a single-electron box can be refrigerated by an AC gate drive [18] at the rate kTf, where T is the temperature and f is the operational frequency. We have demonstrated the principle in DC operation in a so-called heat transistor [19]. The cooler can be operated also by a stochastic drive instead of a harmonic one: this lead to the concept of a Brownian refrigerator of electrons [20].

Recent work in our group on the single-electron effects combined with non-trivial energy currents in NIS junctions led us to consider a novel type of a quantized source of electric current, a so-called hybrid turnstile of electrons [21, 22]. It is an SINIS single-electron transistor, where accurate current plateaus at $I = nef$ can be obtained. Here n is an integer, e is the electron charge and f is the operational frequency. The missing link in the quantum triangle of electronic quantities, a source of current, has been a topic of intense research for more than two decades by now. The first single-electron pumps and turnstiles could demonstrate the principle [23], but they lacked both the sufficiently high current (more than 100 pA needed) and metrological accuracy (better than 10^{-7} needed). An important step forward was achieved by Keller *et al* [24] who managed to pump electrons with error rates smaller than 10^{-8} but still at very low currents (a few picoamperes). Our simple device [21] holds promise for high accuracy and sufficiently high current, at least when operated in a parallelized set-up [25]. One of the interesting features of this device is that its operation can benefit from RF self-refrigeration of the N island according to the proposal in [18]. Experiments on this effect are under way.

On-chip electronic refrigeration has been a topic of basic research for more than a decade by now: for a fairly recent review see [26]. The basic properties of the refrigerator have been verified in experiments and many fascinating phenomena have been proposed and some of them have been observed. A truly practical NIS-based refrigerator is still to be developed. The challenges in this respect lie in the processing techniques, in the fragility of the cooling device and in the interfacing of the cooler and the object to be cooled. It is also still a challenge to extend the operation to both higher (>1 K) and lower ($\ll 50$ mK) temperatures, although both these regimes should be accessible. No doubt we are going to see steps in the progress in both these directions in the near future.

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