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# High-performance electronic cooling with superconducting tunnel junctions

## *Refroidissement électronique à haute performance par jonction tunnel supraconductrice*

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## ABSTRACT

When biased at a voltage just below a superconductor's energy gap, a tunnel junction between this superconductor and a normal metal cools the latter. While the study of such devices has long been focused to structures of submicron size and consequently cooling power in the picowatt range, we have led a thorough study of devices with a large cooling power up to the nanowatt range. Here we describe how their performance can be optimized by using a quasi-particle drain and tuning the cooling junctions' tunnel barrier.

## RÉSUMÉ

Polarisée à une tension juste inférieure à la bande interdite du supraconducteur, une jonction tunnel entre ce supraconducteur et un métal normal peut refroidir ce dernier. Alors que les études de ces dispositifs se sont longtemps concentrées sur des structures de taille submicronique, en conséquence avec des puissances de refroidissement de l'ordre du picowatt, nous avons mené une étude complète de jonctions NIS avec une forte puissance de refroidissement, de l'ordre du nanowatt. Dans cette revue, nous décrivons comment leurs performances peuvent être optimisées par l'ajout d'un drain pour les quasi-particles et l'ajustement de la barrière tunnel des jonctions réfrigérantes.

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## 1. Introduction

Due to Joule heating, an electronic bath in a circuit has usually a temperature higher than that of the bath temperature. The ability of electronic cooling thus opens unusual perspectives, both practical and fundamental.

In general terms, cooling an ensemble of particles can be achieved by replacing high-energy particles by low-energy ones. This selective evaporation scheme requires the implementation of an energy-selective filter. The electronic density of states of a superconductor offers such a filter as it is zero within an energy gap centered at the Fermi level. Electron tunneling through a NIS junction between a normal metal to be cooled and a superconductor is strongly energy-selective: only electrons with an energy (with respect to the Fermi level) higher than the energy gap can escape from the metal and only electrons with an energy below the energy gap can be injected into the same metal. In this way, the electronic temperature of the electronic population as a whole is reduced compared to the environment.

Assuming that the electronic populations in both the normal metal and the superconductor can be described by Fermi distributions $f_N$ and $f_S$ at respective temperatures $T_N$ and $T_S$, the cooling power of a NIS junction biased at a voltage $V$ writes [1–3]:

$$\dot{Q}_{\mathrm{NIS}} = \frac{1}{e^2 R_T} \int_{-\infty}^{\infty} (E - eV) N_S(E) [f_N(E - eV) - f_S(E)] \mathrm{d}E \tag{1}$$

Here, $R_T$ is the tunnel resistance, $N_S$ is the superconductor's density of states, $k_B$ is the Boltzmann constant and $e$ is the electron charge. At the optimum cooling bias $eV \simeq \Delta - 0.66 k_B T_N$ and at low temperature $T_N \ll T_c$, where $T_c$ is the critical temperature, it is:

$$\dot{Q}_{\mathrm{NIS}} \simeq 0.59 \frac{\Delta^2}{e^2 R_T} \left( \frac{k_B T_N}{\Delta} \right)^{3/2} \tag{2}$$

where $\Delta$ is the superconductor's energy gap. The efficiency of the cooler is:

$$\eta = \frac{\dot{Q}_{\mathrm{NIS}}}{IV} \simeq 0.7 \frac{T_N}{T_c} \tag{3}$$

where $I$ is the (charge) current. It amounts to about 20% near $T_N = 350$ mK for aluminum, with a $T_c \simeq 1.3$ K. Aluminum is the standard choice of a superconductor thanks to the high quality of its oxide, which ensures a tunnel barrier without pinholes.

The heat current in a NIS junction [4] is an even function of the voltage bias, which makes that a SINIS junction biased at a double bias (close to $2\Delta$) operates just like a simple NIS junction, but with a double power and most importantly a very good thermal isolation [5]. This makes that SINIS junctions are always preferred to plain NIS junctions.

The smaller the tunnel resistance of a junction, the larger its cooling power, as long as only single-particle tunneling is considered. The contribution of Andreev reflection to the transport can be enhanced by the confinement by disorder and lead to a quite detrimental heat current even though the charge current remains small [6–8]. In terms of cooling, there is thus an optimum for the barrier transparency.

In general, the most significant opposing heat current to $\dot{Q}_{\mathrm{NIS}}$ comes from the electron–phonon interaction in the normal metal. The most accepted form for a metal writes

$$\dot{Q}_{\mathrm{e-ph}} = \Sigma \mathcal{V} (T_N^5 - T_{\mathrm{ph}}^5) \tag{4}$$

where $\Sigma = 2 \times 10^9$ W·K$^{-5}$·m$^{-3}$ for Cu, $\mathcal{V}$ is the volume of the normal island, $T_{\mathrm{ph}}$ is the phonon temperature. If the phonons are weakly coupled with the external world, they can be cooled as a consequence of electron cooling. This effect was first identified through the analysis of electronic coolers' performance [9,10], and then directly identified through the measurement of the phonon temperature [11]. As will be discussed below, phonon cooling can significantly improve the performance of electronic coolers.

Still, the main limitation to electronic cooling is widely recognized as being the imperfect evacuation of quasi-particles created by the tunneling events from the vicinity of the tunnel junctions in the superconducting electrodes [12]. The decay of the quasiparticle density involves quasiparticle recombination retarded by phonon retrapping [13,14]. In this process, two quasiparticles initially recombine to form a Cooper pair, resulting in the creation of a phonon of energy $2\Delta$. This phonon can be subsequently re-absorbed by a Cooper pair, resulting in two new quasiparticles. The $2\Delta$ energy leaves the superconductor when either the phonons or the quasiparticles escape to the bath. The basic strategy to address this issue relies on the presence of quasi-particles traps made of pieces of normal metal coupled with the superconducting electrodes [15–17]. Still, the poor coupling of the traps due to the presence of the same tunnel barrier as in the cooling junctions is a severe limitation. As an interesting alternative, vortices could be created in the superconducting electrodes by applying a magnetic field, and their position was controlled by the geometry of the electrodes [18]. Vortices act as a local trap for quasi-particles, but this approach imposes a magnetic field, which is not compatible with the use of large tunnel junctions.

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