Refrigerators based on NIS tunnel junctions

D. V. Anghel*and J. P. Pekola
Department of Physics, University of Jyväskylä, P.O. Box 35,
40351 Jyväskylä, Finland

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Abstract

We have performed experiments where hot electrons are extracted from a normal metal into a superconductor through a tunnel junction (NIS junction). We have measured the cooling performance of such NIS junctions, especially in the cases where another normal metal electrode, a quasiparticle trap, is attached to the superconductor at different distances from the junction in direct metal-to-metal contact or through an oxide barrier. The direct contact at a submicron distance allows superior thermalisation of the superconductor. We have analysed theoretically the heat transport in this system. From both experiment and theory, it appears that NIS junctions can be used as refrigerators at low temperatures only with quasiparticle traps attached. Configurations with several NIS junctions can be used efficiently for refrigerating purposes.

1 Introduction

Normal metal-insulator-superconducting (NIS) junctions can be used in a variety of applications. This paper is devoted to the cooling properties of such junctions. By placing an insulating layer between a normal metal and a superconductor, one can extract selectively electrons from the normal metal, reducing in this way its temperature. In Fig. 1 it is shown schematically how the hot electrons are extracted from the normal metal through one junction and cold electrons are introduced into it through the other junction. The first part of the cooling process is represented by the tunneling phenomenon through the junction, and is discussed in Section 2. The second part, analyzed in Section 3, concerns the diffusion and trapping of nonequilibrium quasiparticles formed in the superconductor. The general results will be combined in Section 4, where the possibility of constructing coolers using NIS junctions is investigated.

*Permanent address: NIPNE-HH, P.O. Box MG-6, R.O.-76900 Bucureşti-Măgurele, Romania

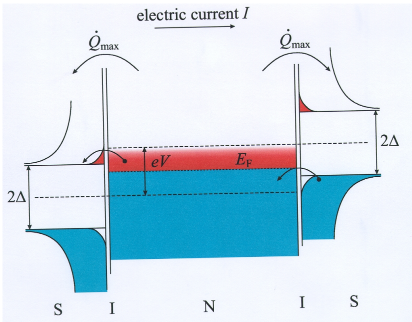

Figure 1: The basics of the cooling process, using a pair of NIS junctions. The hot electrons are extracted from the normal metal (N), through the insulating layer (I) on the left, and deposited into the left superconductor (S). On the right hand side, cold electrons are extracted from the superconductor and deposited into the normal metal. All these processes lead to the reduction of the average energy of the electron gas, i. e. reduction of the temperature in the normal metal. The weak coupling between the electrons and the phonons in a metal, at such low temperatures [1], allows the onset of a nonzero temperature difference between these two subsystems in the process.

2 Tunneling processes in NIS junctions

When a thin insulating material (usually an oxide layer) is placed between a normal metal and a superconductor, forming in this way a NIS junction, the electrical charges can still penetrate from one side to another by tunneling. The thickness of the insulator determines the tunneling probability, which is inversely proportional to the resistance of the junction, R_{T}. The tunneling hamiltonian can be written in the general form [2]:

$$H_T = \sum_{\mathbf{k}_{\mathrm{s}},\mathbf{k}_{\mathrm{n}},\sigma} \{T_{\mathrm{sn}} c^+_{\mathbf{k}_{\mathrm{s}},\sigma} c_{\mathbf{k}_{\mathrm{n}},\sigma} + T^*_{\mathrm{sn}} c^+_{\mathbf{k}_{\mathrm{n}},\sigma} c_{\mathbf{k}_{\mathrm{s}},\sigma}\},$$

where T_{sn} is the tunneling matrix element, while $c^+_{\mathbf{k}_{\mathrm{n}},\sigma}$ and $c^+_{\mathbf{k}_{\mathrm{s}},\sigma}$ are creation operators on the states with momenta $\mathbf{k}_{\mathrm{n}}$ and $\mathbf{k}_{\mathrm{s}}$, respectively, and projection of spin σ. All through this paper, the superscripts "n" and "s" will refer to normal metal and superconductor, respectively. We also make the assumption that the tunneling yields no spin flips. Using the linear transformation of the electron operators, $c_{\mathbf{k}_{\mathrm{s}},\sigma}$ and $c^+_{\mathbf{k}_{\mathrm{s}},\sigma}$, into quasiparticle operators, $\gamma_{\mathbf{k}_{\mathrm{s}}\sigma}$ and $\gamma^+_{\mathbf{k}_{\mathrm{s}}\sigma}$, and the Cooper pair creation and annihilation operators, S^+ and S [3, 4], we can write the terms of the tunneling hamiltonian as in [5]

$$T_{\mathrm{sn}} c^+_{\mathbf{k}_{\mathrm{s}},\sigma} c_{\mathbf{k}_{\mathrm{n}},\sigma} + T^*_{\mathrm{sn}} c^+_{\mathbf{k}_{\mathrm{n}},\sigma} c_{\mathbf{k}_{\mathrm{s}},\sigma} \quad = \quad T_{\mathrm{sn}}(u_{\mathbf{k}_{\mathrm{s}}} \gamma^+_{\mathbf{k}_{\mathrm{s}}\sigma} + v^*_{\mathbf{k}_{\mathrm{s}}} S^+ \gamma_{-\mathbf{k}_{\mathrm{s}}-\sigma}) c_{\mathbf{k}_{\mathrm{n}},\sigma}$$

$$
\begin{aligned}
&+T^*_{\rm sn} c^+_{\mathbf{k}_{\rm n},\sigma}(u^*_{\mathbf{k}_{\rm s}}\gamma_{\mathbf{k}_{\rm s}\sigma} + v_{\mathbf{k}_{\rm s}} S\gamma^+_{-\mathbf{k}_{\rm s}-\sigma}) \\
= &\underbrace{u_{\mathbf{k}_{\rm s}} T_{\rm sn}\gamma^+_{\mathbf{k}_{\rm s}\sigma} c_{\mathbf{k}_{\rm n},\sigma}}_{j_1} + \underbrace{v^*_{\mathbf{k}_{\rm s}} T_{\rm sn} S^+\gamma_{-\mathbf{k}_{\rm s}-\sigma} c_{\mathbf{k}_{\rm n},\sigma}}_{j_4} \\
&+ \underbrace{u^*_{\mathbf{k}_{\rm s}} T^*_{\rm sn} c^+_{\mathbf{k}_{\rm n},\sigma}\gamma_{\mathbf{k}_{\rm s}\sigma}}_{j_3} + \underbrace{v_{\mathbf{k}_{\rm s}} T^*_{\rm sn} c^+_{\mathbf{k}_{\rm n},\sigma} S\gamma^+_{-\mathbf{k}_{\rm s}-\sigma}}_{j_2},
\end{aligned}
$$

where j_1 and j_2 represent the densities in energy of the currents of electrons and holes, respectively, passing from the normal metal into the superconductor, while j_3 and j_4 represent the reverse currents. Expressing the tunneling probability in terms of the normal state tunneling resistance, we obtain the expressions for the four currents, as functions of energy:

$$
\begin{aligned}
j_1(\epsilon) &= g(\epsilon) f_{\rm n}(\epsilon - eV, T_{\rm n})[1 - f_{\rm s}(\epsilon, T_{\rm s})]/e^2 R_{\rm T}, \\
j_2(\epsilon) &= g(\epsilon) f_{\rm n}(\epsilon + eV, T_{\rm n})[1 - f_{\rm s}(\epsilon, T_{\rm s})]/e^2 R_{\rm T}, \\
j_3(\epsilon) &= g(\epsilon)[1 - f_{\rm n}(\epsilon - eV, T_{\rm n})] f_{\rm s}(\epsilon, T_{\rm s})/e^2 R_{\rm T}, \\
j_4(\epsilon) &= g(\epsilon)[1 - f_{\rm n}(\epsilon + eV, T_{\rm n})] f_{\rm s}(\epsilon, T_{\rm s})/e^2 R_{\rm T},
\end{aligned}
\tag{1}
$$

where $f_{\rm n,s}(\epsilon, T_{\rm n,s})$ represent the populations of the electron (in the normal metal) and quasiparticle (in the superconductor) energy levels, at some effective temperatures $T_{\rm n}$ and $T_{\rm s}$, respectively. V is the voltage across the junction and the electron charge is e. The energy ϵ is measured from the Fermi energy in the superconductor and it is always taken in absolute value. Although $f_{\rm n,s}$ may not be Fermi distributions in our case of nonequilibrium [6] we make the assumption that $1 - f_{\rm n}(-\epsilon, T_{\rm n}) = f_{\rm n}(\epsilon, T_{\rm n})$, which is an identity for a Fermi distribution, to transform the expressions that involved negative ϵ. In what follows I shall concentrate on the junction where the flux of electrons is oriented from the normal metal into the superconductor (left side in Fig. 1), where eV is positive. Using Eqs. (1), the particle and excitation fluxes, J_e and J_q, respectively, can be written as

$$
\begin{aligned}
J_e &= \frac{1}{e} I_e = \int_\Delta^\infty (j_1 - j_2 - j_3 + j_4)\, d\epsilon \qquad (2) \\
&= \frac{1}{e^2 R_{\rm T}} \int_\Delta^\infty g(\epsilon)[f_{\rm n}(\epsilon - eV, T_{\rm n}) - f_{\rm n}(\epsilon + eV, T_{\rm n})]\, d\epsilon, \\
J_q &= \int_\Delta^\infty (j_1 + j_2 - j_3 - j_4)\, d\epsilon \qquad (3) \\
&= \frac{1}{e^2 R_{\rm T}} \int_\Delta^\infty g(\epsilon)[f_{\rm n}(\epsilon - eV, T_{\rm n}) + f_{\rm n}(\epsilon + eV, T_{\rm n}) - 2 f_{\rm s}(\epsilon, T_{\rm s})]\, d\epsilon.
\end{aligned}
$$

The power flux transported by the electrons from the normal metal into the superconductor is given by the formula [5]

$$
\begin{aligned}
P_e &= \int_\Delta^\infty [(\epsilon - eV)(j_1 - j_3) - (\epsilon + eV)(j_4 - j_2)]\, d\epsilon \qquad (4) \\
&= \int_\Delta^\infty [\epsilon(j_1 + j_2 - j_3 - j_4) - eV(j_1 - j_2 - j_3 + j_4)]\, d\epsilon.
\end{aligned}
$$

We observe that, while J_e depends only on T_n and is independent of T_s, both J_q and P_e also depend on T_s. As T_s increases, the power extracted from the normal metal decreases, and it turns out that it is important to keep the superconductor at as low temperature as possible, in order to have an efficient cooling of the normal metal. In order to evaluate the temperature of the superconductor, we have to model the diffusion of the quasiparticles into the superconductor. This problem will be discussed in the next section.

3 The diffusion of quasiparticles in superconductors

The cooler consists of a very thin film of normal metal, which is to be cooled, in contact, through an oxide layer, with the superconducting film. The widths of the films vary from about 0.3 μm up to 6 μm. In the case of small junctions, the length of the normal metal film is a few microns, while in the case of large junctions, it is 10 to 30 μm. The length of the superconducting film is considered to be infinite. See Paper IV and citations therein for more details about the experimental design.

From the fact that a quasiparticle excitation, say $\gamma^+_{q\sigma}|BCS\rangle$, where q and σ correspond to the quasiparticle wave-number and spin, respectively, is an eigenstate of the wave-number operator, with eigenvalue q, and from the dispersion equation, one can deduce the energy dependent quasiparticle group velocity, $v(\epsilon, x) = v_\mathrm{F}\sqrt{1-(\Delta(x)/\epsilon)^2}$. The Fermi velocity is denoted by v_F [7, 8]. The diffusion constant $D(\epsilon, x) \equiv (1/2)v(\epsilon, x)a$, where a is the elastic mean free path, follows immediately: $D(\epsilon, x) = (v(\epsilon, x)/v_F)D_\mathrm{n}$ [8]. Here $D_\mathrm{n} = (\rho_\mathrm{n} e^2 \sigma(\epsilon_\mathrm{F}))^{-1}$ is the *normal diffusion constant* of the superconducting film, determined by extrapolating the resistivity ρ_n of its normal state towards zero temperature. Since in the cooling experiments the quasiparticle energies lie close to the gap energy, the diffusion constant is very small. Moreover, the excess population of the quasiparticle levels could decrease the energy gap in the junction region, lowering in this way the cooling performance. As a consequence of this, it was observed in the experiment that if bare superconducting films were used in the construction of the coolers, no appreciable reduction in temperature takes place in the normal metal island (see Paper IV). Therefore, the quasiparticles should be driven away from the junction regions.

In Paper IV we show how one can remove the excess quasiparticle excitations from the regions near the junctions by attaching a semi-infinite normal metal electrode to the superconductor, forming in this way a bilayer structure, which acts as a "trap" for injected hot quasiparticles. To calculate the quasiparticle flux we have to write down the diffusion equation. In all the situations discussed here a film of Cu was used as the normal metal, while the superconducting metal

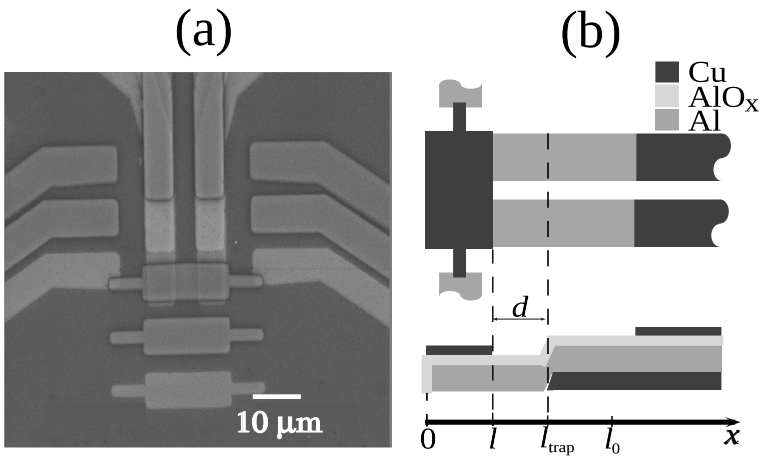

Figure 2: The SEM image **(a)** of a large SINIS cooler used in Paper IV, with junction area $\geq 10\ \mu\mathrm{m}^2$ and its schematic illustration **(b)** from above (up) and in cross-section (down). The cooling junction is in the range $[0, l]$, while the bilayer trap starts at the distance l_{trap} from the origin. The parameter l_0 is defined such that $\Delta(x) = \Delta_{\mathrm{N}}$ for $x \geq l_0$ .The thick line on top of the Al film ((b) down) represents the oxide layer and forms the junction in the range $[0, l]$.

was Al.

Let us consider the NIS structure presented in Fig. 2 (b) (all the geometrical notations will refer to this figure), where the electrons pass from the normal metal into the superconductor. The other junction of the SINIS structure (S, I, and N denote the superconductor, insulator, and normal metal, respectively) can be treated in a similar manner. By $\Delta(x)$ we denote the nonconstant energy gap of the superconductor. We take the gap energy in a bare Al film to be $\Delta_0 = 200\ \mu\mathrm{eV}$, and deep in the bilayer region $\Delta_{\mathrm{N}} < \Delta_0$ because of the proximity effect, in the case of direct metal-to-metal contact between Cu and Al. The excess quasiparticles in the junction region can disappear or change their energy mainly by one of the following processes: interaction with each other, diffusion, recombination, inelastic scattering on the lattice, and tunneling back into the normal metal. All the last three phenomena heat the normal electrode. A monotonic decrease of the energy gap outside of the junction area would enhance the outgoing quasiparticle flux because of the increase of the diffusion constant and of the probability of quasiparticle relaxation by inelastic collisions with the lattice, outside the junction region. A quasiparticle trap through an oxide barrier, similar and close to the junction could be useful in small area (SI)NIS structures, since this would decrease the population of the quasiparticle levels by tunneling

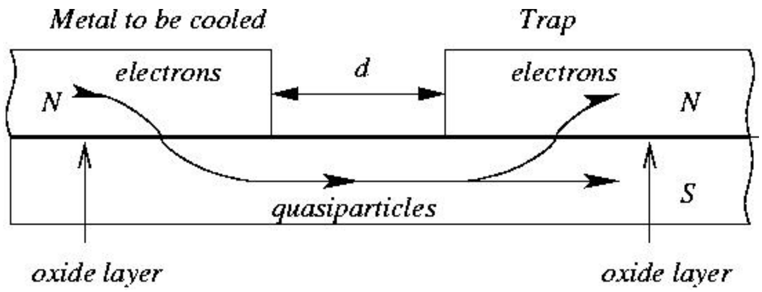

Figure 3: Schematic drawing of the electrons and quasiparticles flow in a cooler with a trap in contact with the superconductor through an oxide layer.

into the normal trap. Taking into account all these effects, we can write the diffusion equation for the population of the quasiparticle energy levels in an interval $[\epsilon, \epsilon + d\epsilon)$ at point x, in the approximation that all the processes are local. Then, if we consider that the quasiparticle distribution at point x can be approximated by the thermal Fermi distribution $f(\epsilon, T_{\rm s}(x))$ corresponding to temperature $T_{\rm s}(x)$ (usually we have $T_{\rm s} > T_{\rm b} > T_{\rm n}$, where $T_{\rm b}$ is the heat bath temperature and $T_{\rm n}$ is the temperature of the electrons in the normal electrode), and integrate over all energies, we obtain a second order nonlinear differential equation for $T_{\rm s}(x)$:

$$\begin{aligned}
&\left(\frac{d^2T_{\rm s}}{dx^2}\right) \int_{\Delta(x)}^{\infty} n_0 D_{\rm n} \left.\frac{\partial f(\epsilon,T_{\rm s})}{\partial T_{\rm s}}\right|_x d\epsilon + \left(\frac{dT_{\rm s}}{dx}\right)^2 \int_{\Delta(x)}^{\infty} n_0 D_{\rm n} \left.\frac{\partial^2 f(\epsilon,T_{\rm s})}{\partial T_{\rm s}^2}\right|_x d\epsilon \\
&- \left(\frac{dT_{\rm s}}{dx}\right) n_0 D_{\rm n} \frac{d\Delta(x)}{dx} \left.\frac{\partial f(\Delta,T_{\rm s})}{dT_{\rm s}}\right|_x \\
&-[\Upsilon_{\rm rec}(T_{\rm s},x) - \Upsilon_{\rm gen}(T_{\rm b},x)] - (\Upsilon_{\rm ph} - \Upsilon_{\rm excit}) \\
&+ \int_{\Delta(x)}^{\infty} j_{\rm q}(V,\epsilon,T_{\rm n},T_{\rm s}(x),x)d\epsilon + \int_{\Delta(x)}^{\infty} j_{\rm q}'(0,\epsilon,T_{\rm s},T_{\rm b},x)d\epsilon = 0.
\end{aligned} \tag{5}$$

The constant $n_0 = w_{\rm s} d_{\rm s}(\sqrt{2m^3}/\pi^2\hbar^3)\sqrt{\epsilon_{\rm F}}$ is the density of electron states at Fermi energy $\epsilon_{\rm F}$, per unit length, along Ox axis. The terms $\Upsilon_{\rm rec} = w_{\rm s} d_{\rm s} R n^2(T_{\rm s}, x)$ [5, 8] and $\Upsilon_{\rm gen} = \Upsilon_{\rm rec}(T_{\rm b}, x)$ account for the quasiparticle recombination and thermal generation rates, respectively. R is the recombination constant and $n(T,x)$ is the quasiparticle density at temperature T and at position x. $(\Upsilon_{\rm ph} - \Upsilon_{\rm excit})$ accounts for the inelastic interaction of quasiparticles with phonons and $j_{\rm q}(V,\epsilon,T_{\rm n},T_s(x),x)$ is the density of the excitation current of energy ϵ through the unit length of the junction, at position x [5]. Therefore note that, formally, $\int_{\Delta(x)}^{\infty} j_{\rm q}(V,\epsilon,T_{\rm n},T_{\rm s},x)d\epsilon = J_q(V,T_{\rm n},T_{\rm s})/l$, where l is the length of the junction. U is the voltage across the junction and $j_{\rm q} = 0$ for $x > l$. In the case of a trap attached to the superconductor through an oxide barrier $j_{\rm q}'(0,\epsilon,T_{\rm s},T_{\rm b},x)$ represents the term corresponding to the tunneling of quasiparticles into the trap. In

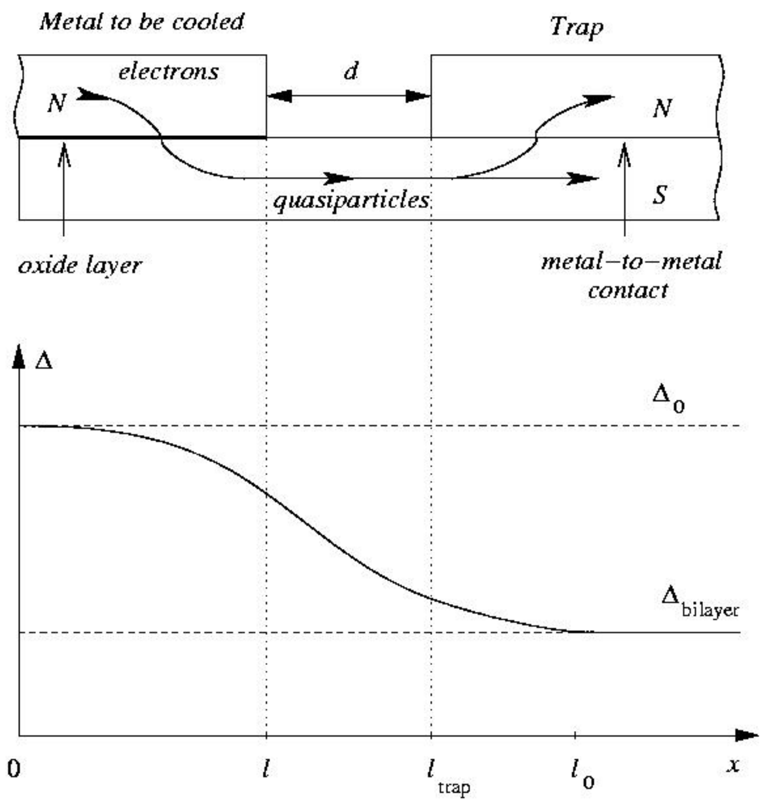

Figure 4: **Top:** schematic drawing of the electrons and quasiparticles flow in a cooler with a trap in metal-to-metal contact with the superconductor. **Bottom:** the variation in space of the energy gap.

the present case the oxide layer in the trap region is identical to the one that forms the junction, $j'_{\rm q}(0,\epsilon,T_{\rm s},T_{\rm b},x\geq l_{\rm trap}) = j_{\rm q}(0,\epsilon,T_{\rm s},T_{\rm b},x\leq l)$ (see Fig. 3). In all the other cases $j'_{\rm q}\equiv 0$. The expansion of the quasiparticle phase-space in the bilayer region for the case of trap in metal-to-metal contact was not taken into account in Eq. (5). In the absence of a rigourous microscopical theory for the density of states in this situation, this can be incorporated by changing the energy gap (Fig. 4).

4 Coolers

To calculate the temperature of the electron gas in the normal metal we have to equate the heat flow to zero. If we neglect the heat dissipated by the electrical

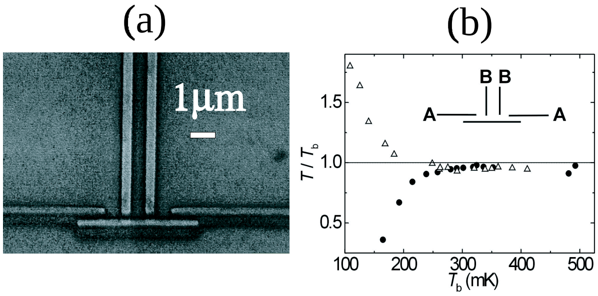

Figure 5: **(a)** A SEM image of a basic SINIS cooler with small junctions, schematically shown as an inset in (b). **(b)** Cooling performance of the sample in (a). Horizontal axis gives the bath temperature. Vertical axis shows the temperature of the normal metal at the optimum cooling bias. The two data sets correspond to: pair B as cooler and pair A thermometer (circles), and pair A as cooler and pair B as thermometer (triangles).

current into the normal metal, the equation obtained is

$$\begin{aligned} &\int_0^l dx \left\{ \int_{\Delta(x)}^{\infty} \epsilon j_{\rm q}(U, \epsilon, T_{\rm n}, T_{\rm s}(x), x), d\epsilon \right. \\ &-k w_{\rm s} d_{\rm s} \Delta(x) [\Upsilon_{\rm rec}(T_{\rm s}, x) - \\ &\left. \Upsilon_{\rm gen}(T_{\rm b}, x)] \right\} - UI - P_{\rm e,ph} = 0, \end{aligned} \tag{6}$$

where $P_{\rm e,ph} = \Sigma w_{\rm n} d_{\rm n} l (T_{\rm b}^5 - T_{\rm n}^5)$. Σ is the electron-phonon coupling constant [1], while $w_{\rm n}$, $d_{\rm n}$, and l are the dimensions of the normal electrode. For copper $\Sigma \approx 4$ nW/K^5 μm^3 [9]. The fraction of the excess recombination phonon energy absorbed by the electrons in the normal metal is k, while I is the total current through the junction, expressed in terms of $T_{\rm n}$, $T_{\rm s}$, U, and $\Delta(x)$ [5]. In cooling experiments the quasiparticle energies lie very close to the gap energy, therefore we can neglect the contribution of the inelastic interaction of the quasiparticles with phonons.

Figure 5 (a) shows a test sample where two types of low power SINIS coolers (S = aluminium of 18 nm thickness, I = aluminium oxide, N = copper of 28 nm thickness) can operate on the same normal metal electrode. The two pairs of junctions, one at the ends of the central normal metal (copper) island (pair A), and another one in the center (pair B), with superconducting electrodes pointing perpendicularly to the normal metal island, can alternatively be used, one as a SINIS cooling pair and the other one as a SINIS thermometer. The junctions have different sizes between the pairs (ca. 1×0.3 μm^2 with total resistance of 12.5 kΩ in A, and ca. 0.4×0.3 μm^2 with 34.4 kΩ in B), but more importantly, the

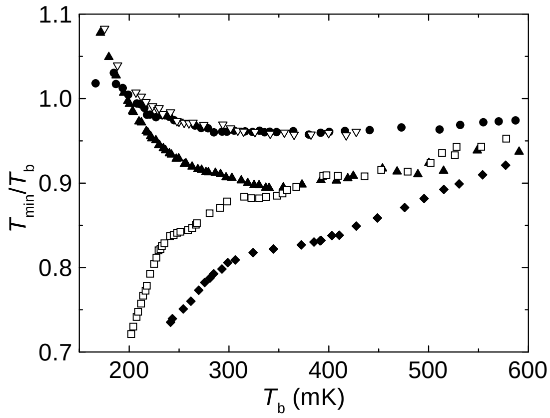

Figure 6: Performance of large junction SINIS coolers. T_b on the horizontal axis is the starting temperature, and T_{min} is the temperature of the normal electrode at the optimum bias for cooling. The five samples are otherwise similar, but the differing parameters are such that: filled circles - no quasiparticle trap connected, $2R_T \simeq 630\ \Omega$; down triangles - quasiparticle trap through an oxide layer at $d = 1\ \mu$m, $2R_T \simeq 280\ \Omega$; up triangles - quasiparticle trap in metal-to-metal contact at $d = 5\ \mu$m, $2R_T \simeq 70\ \Omega$; open squares - quasiparticle trap in metal-to-metal contact at $d = 1\ \mu$m, $2R_T \simeq 230\ \Omega$; filled diamonds - quasiparticle trap in metal-to-metal contact at $d = 1\ \mu$m, $2R_T \simeq 50\ \Omega$. The film thickness of the copper trap, aluminium and the normal metal island was 30 nm, 25 nm and 35 nm, respectively.

superconducting aluminium outside the junctions is covered by a film of copper through the same oxide layer as in the tunnel junctions, differently in the two pairs. In pair B the coverage extends from a distance of about 0.2 μm essentially to infinity, in pair A the similar overlap starts only at a distance of 8 μm. Figure 5 (b) shows the corresponding cooling performances. It is obvious that pair B works better as a cooler. This illustrative data shows that the cooling characteristics depend on the position of the trap and on the geometry of the junction. Yet, as it will turn out below, the trap with an oxide layer between the normal metal and the superconductor is not sufficiently effective for large junctions.

To investigate the efficiency of a normal metal quasiparticle trap, let us analyze different SINIS coolers of nominally 4 - 6 μm × 4 - 6 μm overlap area of the NIS junctions. One should note that this area is typically two orders of magnitude larger than in the conventional electron beam fabricated junctions. Figure 6 presents the results obtained in Paper IV. We show the maximum temperature drop for five different samples of large SINIS cooler junctions. One cannot compare the performance of different samples quantitatively from the main fig-

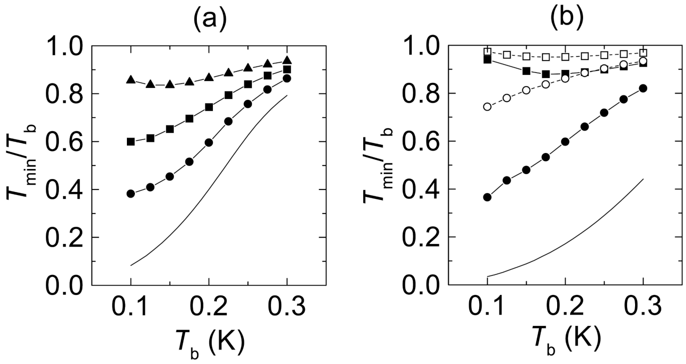

Figure 7: Theoretical results of the minimum temperature of the normal metal, normalized to the bath temperature, vs. bath temperature, for large junctions (the area of one junction is 4×4 μm^2), in the following situations (see Fig. 6 for the corresponding experimental results): **(a)** R_T = 110 Ω and d =1 (circles), 5 (squares) and 10 μm (up triangles). $\Delta_N/\Delta_0 = 1/3$; **(b)** R_T = 30 Ω, Δ_N/Δ_0 = 1/3, and d =1 (filled circles) and 5 μm (filled squares) . For comparison we show the corresponding results for $\Delta_N/\Delta_0 = 1/2$, with open circles and squares. The simple solid lines show the cooling results at optimum bias voltage in the ideal cases when $T_s(x) = T_b$ and $\Delta(x) = \Delta_0$ for all x.

ure directly, because the junction resistance (R_T) varies from sample to sample. Clear qualitative conclusions can, however, be made, especially based on the low temperature behavior. The sample with no quasiparticle trap (filled circles), the one with the trap at a distance d = 1 μm, but with an aluminium oxide layer between the two metals forming the bilayer (open down-triangles), and the one with the trap in metal-to-metal contact at d = 5 μm (filled up-triangles) tend to heat up at $T \leq 200$ mK. The sample shown with open up-triangles had a similar oxide layer between the superconductor and the copper layers to what was used to form the oxide barrier in the (SI)NIS junctions. In the two remaining samples, the one shown with open squares and the one with filled diamonds, the copper-to-aluminium direct metal-to-metal contact is at a distance of less than 1 μm. One can see that in each case the cooling performance is superior down to 200 mK and beyond. The difference in performance between these two samples can be explained qualitatively by the difference of R_T in them. A separate control measurement of a sample with two different values of d from the same fabrication batch were also performed to confirm the conclusion.

We will now briefly outline the theoretical calculations. Since $\Delta(x)$ should depend on the geometry and on $T_s(x)$, one can find all the information regarding the cooling effect by solving Eqs. (5) and (6) self-consistently. Proper boundary

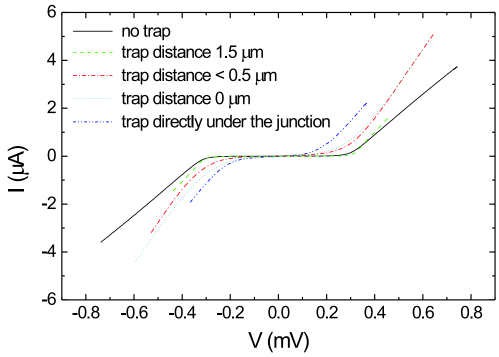

Figure 8: Experimental IV-curves for the configuration with the trap in metal-to-metal contact positioned at the distances indicated in the legend.

conditions for Eq. (5) would be $\partial T_s/\partial x = 0$, at $x = 0$ (zero diffusion current), and $T_s = T_b$ at $x \to \infty$. In the case of a trap in direct metal-to-metal contact we approximate $\Delta(x)$, in the range $0 \leq x \leq l_0$, by the solution of the Ginzburg-Landau equation: $\Delta(x) = -\Delta_0 \tanh\left[(x - (l_0 + y_0))/(\sqrt{2}\xi)\right]$. The parameter y_0 is calculated such that $\Delta(x \geq l_0) = \Delta_N$. We used $R = 26\ \mu\text{m}^3\text{s}^{-1}$, from Ref. [8], and D_n, for large junctions, was calculated to be 140 cm^2s^{-1}, from our measured resistivity of the normal Al film, at 4.2 K. Choosing $\xi = 1\ \mu$m and $l_0 - l_{\text{trap}} = 0.5\ \mu$m (detailed microscopic calculations should give better approximations for these parameters) we calculated the minimum temperature of the electron gas in the normal electrode of the large NIS junction, as a function of T_b. From the experimental IV-curves with different trap positions shown in Fig. 8 we conclude that Δ_N/Δ_0 is between 1/3 and 1/2 for our experimental configuration with trap in metal-to-metal contact. We used these two extreme values in our calculations. The results for the configuration with the trap in metal-to-metal contact positioned at the distances $d = 1$, 5 and 10 μm are shown in Fig. 7. Although the cooling performance varies with parameters like the resistance of the junctions (R_T), diffusivity (D_n) and the function $\Delta(x)$, clear conclusions can be drawn: a trap positioned close to the junction radically improves cooling at low temperatures.

In recent experiments with large junction SINIS structures, the ratio $T_{\min}/T_b$ was reduced down to 0.3 at temperatures around 300 mK, with a cooling power of about 20 pW (see Fig. 9) [10]. The experimental setup is shown in Fig. 10.

Direct numerical calculations and our analytical evaluations [11] show that if there is no trap at all (through oxide barrier or in metal-to-metal contact), neither small nor large junctions can work as refrigerators at low temperatures. The small NIS junctions (as in Fig. 5), with a trap through the oxide barrier positioned close to it, work efficiently as a cooler, while in the case of large NIS

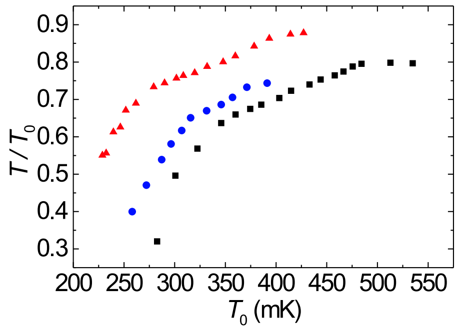

Figure 9: Different cooling performances of large junction SINIS structures. An example of an experimental configuration is shown in Fig. 10. The aspect ratio of the junction is important for the cooling performance, since a smaller l reduces the probability of back tunneling of excitations into the normal metal island [10].

junctions, the thermalization of the superconductor is poor at low temperatures, as observed in the experiment. The theoretical results are shown in Fig. 11.

As a conclusion, we have demonstrated that the excess quasiparticle population, i.e. the heating up of a superconductor, can be significantly reduced by drawing the hot quasiparticles from the junction region into a bilayer trap. The performance of such a trap is superior even with moderately large power levels, when the trap is in direct metal-to-metal contact at a short (< 1 μm) distance from the junction injecting heat (the choice of this distance depends mainly on ξ). In smaller junctions, a trap in contact through an oxide barrier seems sufficient for the purpose. We have modeled the heat balance and flow in the (SI)NIS - quasiparticle trap systems. The theoretical calculations explain the observed phenomena.

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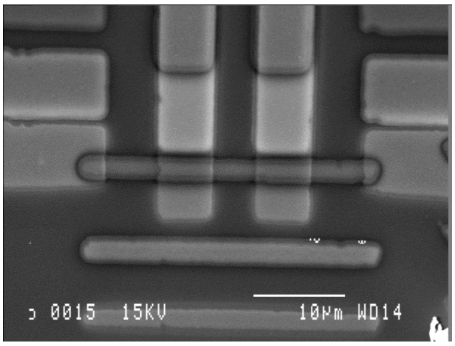

Figure 10: Example of experimental setup. The cooling performances of this type of refrigerators are shown in Fig. 9 [10].

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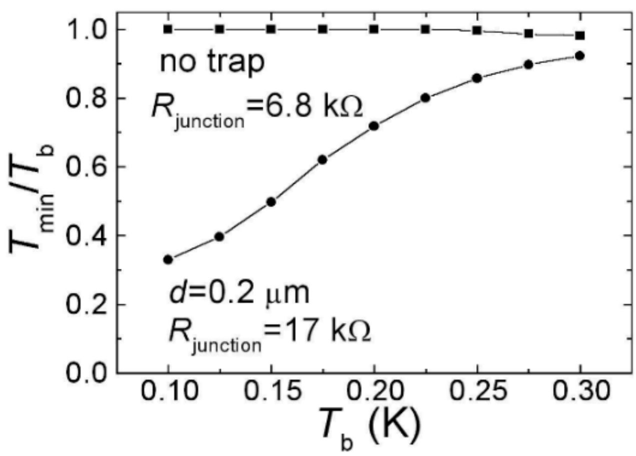

Figure 11: Theoretical calculations of the minimum temperature of the electron gas in the normal metal of a cooler with small junctions. The junction parameters, as it is shown on the figure, correspond to the pairs AA and BB of junctions in Fig. 5.