Efficient Peltier refrigeration by a pair of normal metal/insulator/superconductor junctions

M.M. Leivo and J.P. Pekola

Department of Physics, University of Jyväskylä, P.O. Box 35, 40351 Jyväskylä, Finland

D.V. Averin

Department of Physics, SUNY Stony Brook, NY 11794

Abstract

We suggest and demonstrate in experiment that two normal metal/insulator/superconductor (NIS) tunnel junctions combined in series to form a symmetric SINIS structure can operate as an efficient Peltier refrigerator. Specifically, it is shown that the SINIS structure with normal-state junction resistances 1.0 and 1.1 kΩ is capable of reaching a temperature of about 100 mK starting from 300 mK. We estimate the corresponding cooling power to be 1.5 pW per total junction area of 0.8 µm² at $T = 300$ mK.
Recently it was shown [1] that the Peltier effect in normal metal /insulator/ superconductor (NIS) junctions can be used to cool electrons in the normal electrode of the junction below lattice temperature. The cooling arises due to the energy gap in the superconductor, because of which quasiparticles with higher energy are removed more effectively from the normal metal than quasiparticles with lower energy. The decrease in electron temperature demonstrated in this first experiment was, however, limited to about 10% of the starting temperature. There are two possible reasons for this. The first and most obvious, is that the resistance of the refrigerator junction was relatively large leading to low cooling power. The second possible reason is heat leakage through the SN contact used to bias the refrigerator. Nominally, an ideal SN contact with large electron transparency should be able to provide electric conductance without thermal conductance at low temperatures. However both finite temperature and finite subgap density of states in a superconductor lead to non-zero thermal conductance of the biasing contact which degrades the refrigerator performance. This poses the problem of how to bias the refrigerator without compromising its thermal insulation.

In what follows we address these two problems and show that once they are solved the refrigerator performance is improved dramatically. In particular, we show that such a refrigerator is capable of reaching temperatures of about 100 mK starting from 300 mK. This brings the NIS refrigerators quite close to practical applications, for instance, in cooling space-based infrared detectors [2].

The problem of refrigerator junction resistance can be alleviated to some degree in a straightforward way either by increasing the junction area or decreasing the specific resistance of the insulator barrier. Because of the limitations of the fabrication method (see below) the junction area could not be increased by much, so that the only option available to us was to make the insulator barrier thinner. Although it is a challenging technological problem to push this process to its limit, we could conveniently reduce the specific resistance of the junctions to about $0.3 \, \text{k}\Omega \times \mu\text{m}^2$.

It is less obvious how to solve the second problem of heat leakage through the biasing junction. The solution we suggest here is to combine two NIS junctions in series to form
a symmetric SINIS structure. Since the heat current in the NIS junction is a symmetric function of the bias voltage $V$, the heat flows out of the normal electrode regardless of the direction of the electric current if the junction is biased near the tunneling threshold, $V \simeq \pm \Delta/e$. This means that in a symmetric SINIS structure we can realize the conditions when the electric current flows into the normal electrode through one junction and out through the other one, while the heat flows out of the normal electrode through both junctions. In this way the heat leakage into the normal electrode of the structure is minimized. The experiment with the SINIS structures described below supports this idea.

We begin by briefly outlining the basic theoretical concepts concerning the heat flow in the NIS junctions. Under typical conditions when the transparency of the insulator barrier is small, the heat current $P$ out of the normal electrode (cooling power) of an individual NIS junction is:

$$P(V) = \frac{1}{e^2 R_T} \int_{-\infty}^{+\infty} d\epsilon N(\epsilon)(\epsilon - eV)[f_1(\epsilon - eV) - f_2(\epsilon)],$$  \hspace{1cm} (1)

where $R_T$ is the normal-state tunneling resistance of the barrier, $f_j$ is an equilibrium distribution of electrons in the $j$th electrode, and $N(\epsilon) = \Theta(\epsilon^2 - \Delta^2) \frac{\epsilon}{\sqrt{\epsilon^2 - \Delta^2}}$ is the density of states in the superconductor. From eq. (1) we can deduce several properties of the cooling power $P$. First of all, by changing the integration variable $\epsilon \rightarrow -\epsilon$ we prove that for equal temperatures of the two electrodes $P$ is indeed a symmetric function of the bias voltage, $P(-V) = P(V)$. Plotting eq. (1) numerically one can see that $P$ is maximum at the optimal bias points $V \simeq \pm \Delta/e$. The optimal value of $P$ depends on temperature and is maximum at $k_B T \simeq 0.3\Delta$, when it reaches $0.06\Delta^2/e^2 R_T$, and decreases at lower temperatures as $(k_B T/\Delta)^{3/2}$ [2]. (The last conclusion is different from the $T^2$ law obtained in Ref. [1].) Specifically, at $V = \Delta/e$ (i.e., quite close to the optimal bias voltage) one can get from eq. (1):

$$P(\Delta/e) = \frac{\sqrt{\pi}(\sqrt{2} - 1)}{4} \zeta(3/2) \frac{\Delta^2}{e^2 R_T} \left(\frac{k_B T}{\Delta}\right)^{3/2} \simeq 0.48 \frac{\Delta^2}{e^2 R_T} \left(\frac{k_B T}{\Delta}\right)^{3/2}. \hspace{1cm} (2)$$

Figures 1a and 1b show, respectively, a schematic diagram of the SINIS structures studied in our experiments and the corresponding AFM image of the structure. Four tunnel junctions
were fabricated around a normal metal (Cu) central electrode and four superconducting (Al) external electrodes. The electrodes were made with electron beam lithography using the shadow mask evaporation technique. The tunnel junctions were formed by oxidation in pure oxygen between the two metallization steps. Two junctions at the edges with larger areas were used for refrigeration, while the pair of smaller junctions in the middle was used as a thermometer. A floating measurement of voltage across the two thermometer junctions at a constant bias current was used to measure temperature in the same way as in the simpler one junction case [4].

Prior to our experiments with the SINIS refrigerator we repeated measurements in the geometry of Nahum et al. [1]. In our case the refrigerating junction had a resistance of $R_T = 7.8 \, \text{k}\Omega$, the copper island was 10 $\mu\text{m}$ long, 0.3 $\mu\text{m}$ wide and 35 nm thick. Results of the measurements of the electron temperature in the island as a function of refrigerator voltage $V_{\text{refr}}$ for several starting temperatures at $V_{\text{refr}} = 0$ are shown in Fig. 2. We see that only a few per cent refrigeration can be obtained, as expected.

Solid lines in Fig. 2 represent a theoretical fit obtained within the standard model of electron energy relaxation [6–8]. Within this model, we assume that the electron-electron collision rate is large so that the electrons maintain an equilibrium distribution characterized by the temperature $T$, which is in general different from the lattice temperature $T_l$. The rate of energy transfer from electrons to phonons is then [7]: $P_l = \Sigma U (T^5 - T_l^5)$, where $\Sigma$ is a constant which depends on the strength of electron-phonon coupling, and $U$ is the volume of the island. Another element of the fitting process is a heat conductance $\kappa$ of the biasing SN contact. (For simplicity, we neglect temperature dependence of $\kappa$, since the temperature range of interest in Fig. 2 is not very large.) The value of the superconductor gap $\Delta$ is almost fixed by the position of the temperature dips in the refrigeration curves (Fig. 2) and is taken to be 155 $\mu\text{eV}$ for this sample. Solving numerically the equation $P = P_l + \kappa(T - T_l)$, where $P$ is the cooling power [1] we can calculate $T$ as a function of $V_{\text{refr}}$. The fit in Fig. 2 is obtained in this way with $\Sigma = 0.9 \, \text{nW/K}^5 \mu\text{m}^3$ and $\kappa = 8 \, \text{pW/K}$. For comparison, the dashed line shows the fit obtained for the lowest-temperature curve without $\kappa$; in this case
\[ \Sigma = 1.4 \text{ nW/K}^5 \mu \text{m}^3. \] Although there is no drastic disagreement with the data even in this case, we see that \( \kappa \) improves the fit considerably.

To see whether the value of the heat conductance \( \kappa \) deduced from the fit in Fig. 2 is reasonable, we calculated the heat conductance of the SN contact with perfect electron transparency at low temperatures, using the method developed in [8,3]:

\[
\kappa = \frac{2\Delta}{e^2 R_N} \left( \frac{2\pi \Delta}{k_B T} \right)^{1/2} \exp\left(-\frac{\Delta}{k_B T}\right). \tag{3}
\]

Making use of the gap value and temperature corresponding to Fig. 2 we get from this equation that \( \kappa = 8 \text{ pW/K} \) corresponds to the normal-state contact resistance \( R_N \) on the order of 100 Ohm, which is of the same order of magnitude as in the experiment.

Figure 3 shows our main results with the SINIS refrigerator of Fig. 1. The two refrigerating junctions had resistances \( R_T = 1.0 \) and 1.1 k\( \Omega \), respectively, and the island was 5 \( \mu \text{m} \) long, 0.3 \( \mu \text{m} \) wide, and 35 nm thick. In Fig. 3 we see several refrigeration curves starting at various ambient temperatures at \( V_{\text{refr}} = 0 \). Note that maximum cooling power is now obtained at \( V_{\text{refr}} \approx 2\Delta/e \) because of two junctions involved. From the position of the temperature dips we get \( \Delta = 180 \mu \text{eV} \). We see that the drop in temperature is immensely improved over that of the single junction configuration. Solid lines in Fig. 3 show the theoretical fit which was obtained within the same model as for the single-junction configuration with the two modifications. We do not have heat conductance \( \kappa \) this time, and we need to solve the balance equations simultaneously for the energy and electric current in order to determine the electric potential of the island. The best fit shown in Fig. 3 corresponds to \( \Sigma = 4 \text{ nW/K}^5 \mu \text{m}^3. \) The fit can be classified as reasonable, although there are some obvious discrepancies between the data and the theory. Possible origins of these discrepancies include an oversimplified model of electron-phonon heat transfer on the theory side, and poor calibration of the thermometer toward higher temperatures on the experimental side. The inset in Fig. 3 shows the maximum cooling power as a function of temperature deduced from this fit, together with the analytical dependence obtained by summing eq. (2) over the two junctions. We see that the simple analytical expression (2) gives a very accurate description of the lower-temperature cooling power.
We note in passing that the experiment described above provides a more transparent alternative interpretation of the previous experiments on the enhancement of superconductivity in the SIS'IS structures [9]. It implies that the reason for the stimulation of superconductivity in the central electrode of the SIS'IS structure might not be the formation of the non-equilibrium distribution of quasiparticles inside this electrode [9,10], but simply a decrease in its temperature.

Before concluding we would like to mention that the next step in the development of a practical NIS refrigerator could be further optimization of the refrigerator performance with respect to the resistance $R_T$ of the insulator barrier. As we saw above, the cooling power of the refrigerator increases with decreasing $R_T$. For a fixed junction area this trend would continue only up to an optimal resistance, at which point the transport starts to be dominated by Andreev reflection [3]. The theoretical limit for the maximum cooling power density is on the order of $10^{-8}$ $W/\mu m^2$ for aluminum junctions and should be reached in the junctions with unrealistically low specific resistances on the order of $10^{-2}$ $\Omega \times \mu m^2$. In practice the limiting factors will be the technological ability to fabricate uniform tunnel barriers with high transparency, and, conceivably, the heat leakage through these tunnel barriers to the central island.

In conclusion, we have shown that the nominally-symmetric SINIS structure can be used as an efficient Peltier refrigerator. One of the advantages of the symmetric structure is that it is easier to fabricate than the asymmetric single-junction configuration. Besides this, SINIS structure provides more efficient thermal insulation of the central electrode, which allowed us to demonstrate a temperature drop of about 200 mK starting from 300 mK. The achieved cooling power density was approximately 2 pW/$\mu m^2$, with the total power being 1.5 pW at $T = 300$ mK.

The authors gratefully acknowledge useful discussions with K. Likharev and M. Paalanen. This work was supported in part by the Academy of Finland and ONR grant # N00014-95-1-0762.
REFERENCES

[1] M. Nahum, T.M. Eiles, and J.M. Martinis, Appl. Phys. Lett. 65, 3123 (1994).

[2] For space cryogenic applications, see, e.g., C. Hagmann, D.J. Benford, and P.L. Richards, Cryogenics 34, 213 (1994); and a special issue of Cryogenics 34, No. 5 (1994).

[3] A. Bardas and D. Averin, Phys. Rev. B 52 (1995), to be published.

[4] M. Nahum and J.M. Martinis, Appl. Phys. Lett. 63, 3075 (1993).

[5] M.L. Roukes, M.R. Freeman, R.S. Germain, R.C. Richardson, and M.B. Ketchen, Phys. Rev. Lett. 55, 422 (1985).

[6] F.C. Wellstood, C. Urbina, and J. Clarke, Appl. Phys. Lett. 54, 2599 (1989).

[7] R.L. Kautz, G. Zimmerli, and J.M. Martinis, J. Appl. Phys. 73, 2386 (1993).

[8] G.E. Blonder, M. Tinkham, and T.M. Klapwijk, Phys. Rev. B 25, 4515 (1982).

[9] M.G. Blamire, E.C.G. Kirk, J.E. Evetts, and T.M. Klapwijk, Phys. Rev. Lett. 66, 220 (1991); D.R. Helsinga and T.M. Klapwijk, Phys. Rev. B 47, 5157 (1993).

[10] A.V. Zaitsev, JETP Lett. 55, 66 (1992).
FIGURES

Figure 1. (a) The schematics of the SINIS refrigerator used in the measurements, and (b) an AFM image of the actual structure.

Figure 2. Results of the NIS single junction experiment: temperature $T$ [mK] of the N-electrode versus refrigerator voltage $V_{refr}$ [$\mu$V]. Dots and solid lines show, respectively, experimental data and the theoretical fit including heat conductance of the biasing contact. For comparison, the dashed line shows the fit without the heat conductance.

Figure 3. SINIS refrigerator performance at various starting temperatures. Notations are the same as in Fig. 2. Dots are the experimental data, while the solid lines show the theoretical fit with one fitting parameter $\Sigma$ for all curves. The inset shows the cooling power $P$ [pW] from the fits (dots), together with the analytical result from eq. (2).