Microrefrigeration by a pair of normal metal/ insulator/superconductor junctions

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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 μm^2 at $T = 300$ mK. This cooling power density implies that scaling of junction area up to about 1 mm^2 should bring the cooling power in the μW range.

Introduction

Recently it was shown [1] that in the sub-Kelvin temperature range 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 mechanism of the cooling in the NIS contacts is the same as that of the well-known Peltier effect in metal/semiconductor contacts – see, e.g., [2]. Due to the energy gap in the superconductor, electrons with higher energies (above the gap) are removed from the normal metal more effectively than those with lower energies. This makes the electron energy distribution sharper, thus decreasing the effective temperature of electron gas in the normal metal. 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.

The aim of the present work was to address these two problems and to show that once they are solved the refrigerator performance is improved dramatically. In particular, we show that refrigerator with two NIS junctions in series 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 [3].

The problem of large specific refrigerator junction resistance can be alleviated to some degree in a straightforward way by making 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 kΩ $\times$ μm^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.

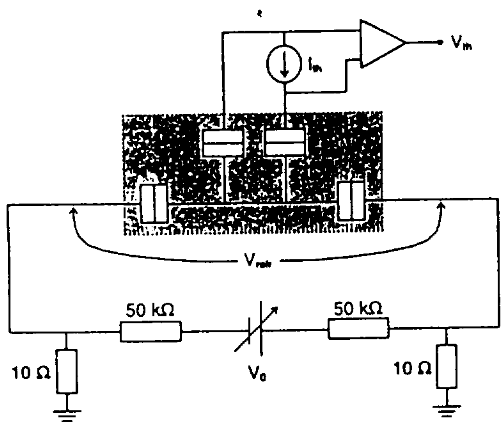
Basic concepts and refrigerator structure

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:

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

where R_T is the normal-state tunneling resistance of the barrier, f_j is an equilibrium distribution of electrons in the jth electrode, and $N(\epsilon) = \Theta(\epsilon^2 - \Delta^2)\,|\epsilon|\,/\sqrt{\epsilon^2 - \Delta^2}$ 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 $(k_B T/\Delta)^{3/2}$ [4]. Specifically, at $V = \Delta/e$ (i.e., quite close to the optimal bias voltage) one can get from eq. (1):

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



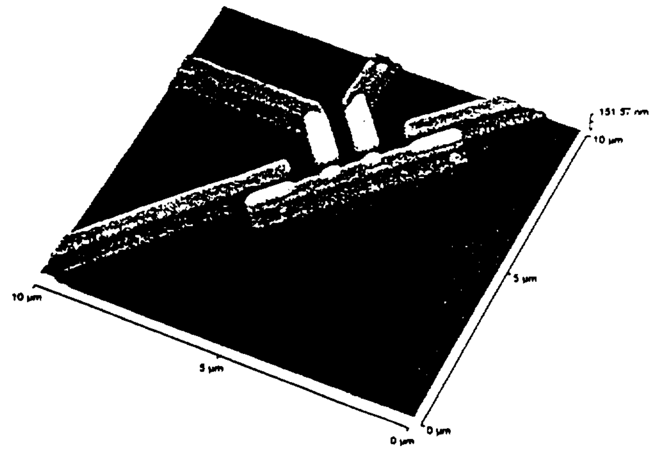


Figure 1. (a) The schematics of the SINIS refrigerator used in the measurements, and (b) an AFM image of the actual structure.

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 [5].

Single-junction refrigerator

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 $R_T = 7.8$ kΩ, the copper island was 10 μm long, 0.3 μm wide and 35 nm thick. Results of the measurements of the electron temperature in the island as a function of refrigerator voltage V_{refr} for several starting temperatures at $V_{refr} = 0$ are shown in Fig. 2. We see that only a few per cent refrigeration can be obtained, as expected.

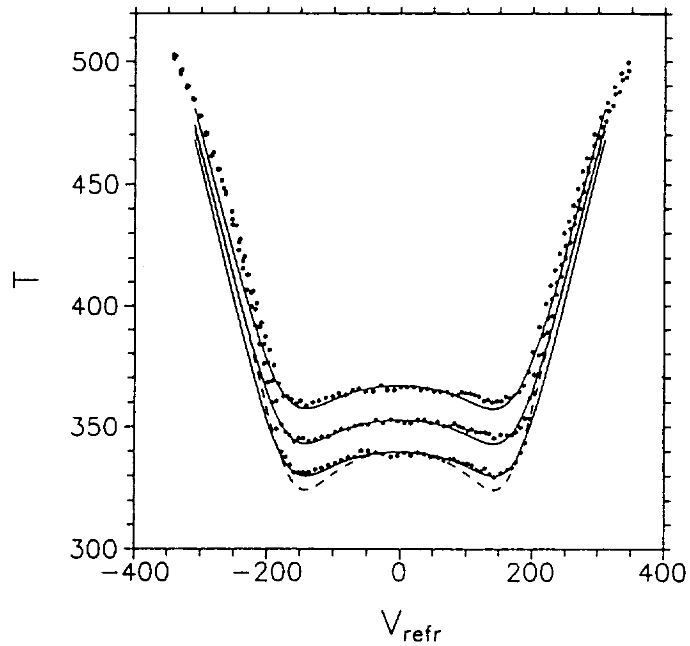


Figure 2. Results of the NIS single junction experiment: temperature T [mK] of the N-electrode versus refrigerator voltage V_{refr} [μV]. Dots and solid lines show, respectively, experimental data and the theoretical fit including heat conductance of the biasing contact. For comparison, the dashed line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

Solid lines in Fig. 2 represent a theoretical fit obtained within the standard model of electron energy relaxation [7-9]. 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 [8]: $P_l = \Sigma U(T^5 - T_l^5)$, where Σ 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 κ of the biasing SN contact. (For simplicity, we neglect temperature dependence of κ, since the temperature range of interest in Fig. 2 is not very large.) The value of the superconductor gap Δ is almost fixed by the position of the temperature dips in the refrigeration curves (Fig. 2) and is taken to be 155 μeV 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_{refr}. The fit in Fig. 2 is obtained in this way with $\Sigma = 0.9$ nW/K^5 μm^3 and $\kappa = 8$ pW/K. For comparison, the dashed line shows the fit obtained for the lowest-temperature curve without κ; in this case $\Sigma = 1.4$ nW/K^5 μm^3. Although there is no drastic disagreement with the data even in this case, we see that κ improves the fit considerably.

To see whether the value of the heat conductance κ 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 [9,4]. In this approach, the heat current J in the contact can be written as follows:

$$J = \frac{1}{e^2 R_N} \int d\epsilon (\epsilon - eV)[f_1(\epsilon - eV) - A(\epsilon) f_1(\epsilon + eV) - (1 - A(\epsilon)) f_2(\epsilon)] , \qquad (3)$$

where R_N is the normal-state contact resistance, functions $f_j(\epsilon)$ are introduced in eq. (1), and $A(\epsilon)$ is the probability of Andreev reflection from the ideal NS interface:

$$A(\epsilon) = \begin{cases} (\mid \epsilon \mid - (\epsilon^2 - \Delta^2)^{1/2})^2/\Delta^2 , & \mid \epsilon \mid > \Delta , \\ 1 , & \mid \epsilon \mid < \Delta . \end{cases}$$

At low temperatures $k_B T \ll \Delta$ and vanishing bias voltage V eq. (3) gives for the linear heat conductance κ:

$$\kappa = \frac{2\Delta}{e^2 R_N} (\frac{2\pi\Delta}{k_B T})^{1/2} \exp(-\frac{\Delta}{k_B T}) . \qquad (4)$$

Making use of the gap value and temperature corresponding to Fig. 2 we get from this equation that κ = 8 pW/K corresponds to R_N on the order of 100 Ohm, which is the same order of magnitude as in the experiment.

Double-junction refrigerator

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 kΩ, respectively, and the island was 5 μm long, 0.3 μm wide, and 35 nm thick. In Fig. 3 we see several refrigeration curves starting at various ambient temperatures at $V_{refr} = 0$. Note that maximum cooling power is now obtained at $V_{refr} \simeq 2\Delta/e$ because of two junctions involved. From the position of the temperature dips we get $\Delta = 180$ μeV. 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 κ 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 Σ = 4 nW/K^5 μm^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.

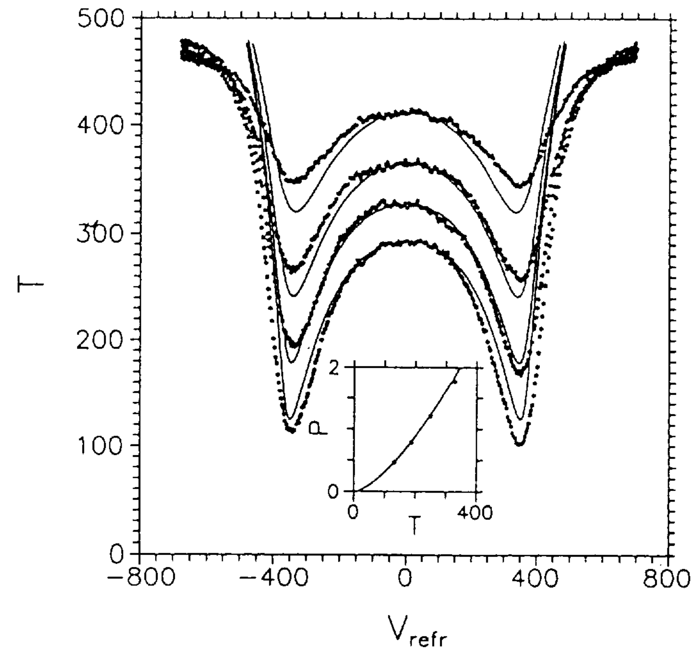


Figure 3. SINIS refrigerator performance at various starting temperatures. Notations are the same as in Fig. 2. Dots are the experimental data, while the solid lines show the theoretical fit with one fitting parameter Σ for all curves. The inset shows the cooling power P [pW] from the fits (dots), together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

We must stress that Fig. 3 shows electron, not lattice temperature. By cooling only electron gas we avoid the problem of parasitic phonon heat conductance through refrigerating junctions. (Electron heat conduction due to tunneling plays a minor role and was accounted for in our model.) If we would try to cool down the normal island as a whole, the phonon heat conduction through the insulator barrier would become important limiting factor also in our refrigerator. In order to estimate the magnitude P_{ph} of the parasitic phonon heat flow through the tunnel junctions we note that neither the thin insulator layer of the junction nor the difference between parameters of the junction electrodes (aluminum and copper in our experiment) give rise to substantial reflection coefficient of the large-wavelength phonons relevant at low temperatures. Therefore we can estimate P_{ph} as the flow of energy associated with ballistic propagation of acoustic phonons:

$$P_{ph} = \frac{\pi^2 (k_B T)^4}{120\hbar^3}\left(\frac{1}{c_{\parallel}^2} + \frac{2}{c_{\perp}^2}\right),$$

where $c_{\parallel}$ and $c_{\perp}$ are longitudinal and traversal sound velocities. For aluminum at T=1 K this equation gives the power density $P_{ph} \simeq 0.6$ nW/μm^2. Comparing this with the cooling power of our refrigerator we see that the refrigerator can cool the normal island as a whole only for starting temperatures not greater than 0.3 K. Decrease in tunnel resistance of the refrigerating junctions could shift this temperature limit to few Kelvins.

Conclusion

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/μm^2, with the total power being 1.5 pW at $T = 300$ mK.

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 [4]. The theoretical limit for the maximum cooling power density is on the order of 10^{-8} W/μm^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.

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