Electronic Micro-Refrigerator Based on a Normal-Insulator-Superconductor Tunnel Junction

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Abstract

We present measurements on a novel electronic micro-refrigerator that can cool conduction electrons significantly below the lattice temperature. A normal-insulator-superconductor tunnel junction is used to extract electrons from the normal metal electrode whose energy is higher than the Fermi energy. Electrons with an average energy equal to the Fermi energy are returned to the metal by a superconducting contact. Consequently, the high-energy thermal excitations are removed from the normal metal, thus cooling the electrons. For lattice temperatures higher than 100 mK the data can be explained by a simple theory incorporating the BCS density of states in the superconducting electrode and the coupling between electrons and phonons. At lower temperatures our measurement suggests that the electron energies in the normal electrode depart strongly from an equilibrium distribution.

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At low temperatures the conduction electrons in metals become thermally decoupled from the lattice as the number of phonons decreases. Consequently, the electrons can assume an equilibrium energy distribution with a different temperature from that of the lattice. To date, most experiments have probed hot-electron effects, where the electrons are heated above the lattice by passing a current through a resistive metal film.[1-3] In this letter we demonstrate how the unique thermal transport properties of a normal-insulator-superconductor (NIS) tunnel junction can be used to manipulate the Fermi-Dirac distribution of electrons in the normal electrode in order to cool them well below the lattice.[4] We find that, for lattice temperatures higher than 100 mK, the measured electron temperature is predicted by a simple theory incorporating the BCS density of states in the superconducting electrode and the coupling between electrons and phonons. However, at lower temperatures, our measurement suggests that the electron energies in the normal electrode depart strongly from an equilibrium distribution.

A related device, utilizing a double junction configuration (SINIS), was previously used to enhance the critical-temperature of a thin aluminum film forming the normal electrode.[5] Our electron-refrigerator differs from the SINIS device in several important aspects. First, the structure of the electron refrigerator (SNIS) is simpler and enables an independent and direct measurement of the electron temperature in the normal electrode. The SINIS experiments could not measure the temperature directly and thus relied upon a theoretical fit to explain the data. Furthermore, in contrast to previous work, we explain the data by considering both the thermal transport properties of the tunnel junction and the transfer of energy to the lattice phonons.

The NIS refrigerator is shown schematically in Fig.1(a). It consists of a normal metal strip which is connected to a superconducting contact. The metal strip also forms the normal electrode for two NIS tunnel junctions, one of which is the electron refrigerator and the other is a sensitive electron thermometer.[3] The refrigerator junction is electrically biased so that only electrons whose energy E is larger than the Fermi energy E_F are removed from the metal strip, as shown in Fig. 1(b). Electrons with an average energy equal to the Fermi energy are returned to the strip through the superconducting contact. The net result of this manipulation is to remove the high-energy thermal excitations from the electron population, thus cooling the electrons. As discussed below, the thermometer junction is biased so that it does not affect the electron temperature in the normal electrode but still has sufficient sensitivity to measure the electron temperature.

In order to understand the operating principles of the refrigerator we first review its main components. The NIS junction is used here both as a thermometer and a refrigerator for the electrons. The current-voltage (I-V) characteristic of the junction depends only on the temperature T of electrons in the normal metal electrode and is independent of the temperature of the superconducting electrode.[6] For our experimental parameters there are very few thermal excitations in the superconducting electrode since its energy gap Δ is much larger than the thermal energy of excitations. Consequently, the dominant contribution to the current is by electron tunneling from the normal to the superconducting electrode, as shown in Fig. 1(b). For $eV > 0$ the current is given by[6]

$$I = \frac{1}{e^2R_N}\int_{\Delta}^{\infty}\frac{1}{\exp[(E - eV)/k_BT] + 1}\,\frac{E}{\sqrt{E^2 - \Delta^2}}\,dE. \qquad (1)$$

Here R_N is the normal state resistance of the junction.[7] When $(\Delta\text{-}eV) > k_BT$, then $I \approx I_o\exp[-(\Delta\text{-}eV)/k_BT]$, where $I_o = (2eR_N)^{-1}(2\pi\Delta k_BT)^{1/2}$. If the junction is biased at a constant current then the temperature responsivity $dV/dT \approx -(k_B/e)\ln(I_o/I)$. For typical values of bias current we calculate $dV/dT = -0.4\ \mu V/mK$.

The thermal transport properties of the NIS junction can be understood by considering the energy transferred by tunneling. When $eV < \Delta$ only electrons with energy $E > E_F$ can tunnel from the normal electrode. This process removes the high-energy thermal excitations from the normal electrode thus cooling the electrons. When $eV > \Delta$ electrons with $E < E_F$ are also allowed to tunnel and subsequently deposit energy into the normal electrode. The calculation of the power transfer P_N from the normal electrode is similar to that of the tunneling current in Eq. (1), except that here the energy (E-eV) transferred by each electron is taken into account:[8]

$$P_N = \frac{1}{e^2 R_N} \int_{\Delta}^{\infty} (E - eV) \frac{1}{\exp[(E - eV)/k_B T] + 1} \frac{E}{\sqrt{E^2 - \Delta^2}} \, dE. \qquad (2)$$

The maximum cooling power $P_{max} \approx -(k_B T)^2/(e^2 R_N)$ occurs when $eV = \Delta$. For $eV < (\Delta - k_B T)$ the cooling power is approximately $(eV-\Delta)(I/e)$, whereas for $eV > (\Delta + k_B T)$, a power $(eV-\Delta)(I/e)$ is dissipated in the normal electrode. The cooling efficiency of the refrigerator is $|P_N|/IV \approx k_B T/\Delta$ for $eV = \Delta$, and is typically less than 10%. The superconducting electrode dissipates a power $P_S = IV - P_N$ in the form of phonons produced by the recombination of quasiparticle excitations to form Cooper pairs. In our configuration, where the density of quasiparticles is small, this energy does not leak back into the normal metal.

A second component of the electron refrigerator is the normal-superconducting (NS) contact which, through the process of Andreev reflection, allows electrical but not thermal contact to be made with the normal electrode.[9] When current is passed through the NS interface, a Cooper pair in the superconductor combines with a hole from the normal metal and produces an electron which subsequently carries the current in the applied field. The electron is injected into the metal with an average energy equal to E_F and hence does not add energy to the normal electrode.

In addition to the cooling process discussed above it is also necessary to consider those mechanisms which deposit energy in the normal metal. In our configuration there are two sources of energy input. The first is due to the thermal coupling between electrons and the lattice, which occurs by the absorption and emission of phonons. The power transfer between the two systems is given by $P_{e\text{-}p} = \Sigma U(T_p^5 - T^5)$, where T_p is the lattice temperature, U is the volume of the metal, and $\Sigma \approx 2$ nWK^{-5}μm^{-3} is a material-dependent parameter.[2] A second source of energy input is due to the power which is dissipated in the resistance of the normal electrode by the refrigerator and thermometer currents. However, for our configuration this Joule heating contribution is negligible. The electron temperature in the normal electrode is thus predicted from the energy balance equation, $P_N + P_{e\text{-}p} = 0$.

The refrigerator was fabricated on a silicon substrate using conventional electron-beam lithography and triple-angle evaporation.[10] Two superconducting aluminum electrodes, 750 nm thick and 0.5 μm wide, were electron-beam evaporated and subsequently oxidized in 33 Pa (250 mTorr) of O_2 for 5 min to form the tunnel barriers. The normal metal copper electrode was subsequently evaporated into a 0.5 μm wide, 10 μm long, and 80 nm thick strip. The superconducting contact consisted of a 250 nm thick 0.5 μm wide lead (Pb) strip which was thermally evaporated in a separate vacuum system. The normal state resistances of the thermometer and refrigerator junctions were 8 kΩ and 10 kΩ respectively. From previous measurements we estimate the resistance of the copper strip to be 10 Ω. The refrigerator can also be fabricated using conventional photolithography or shadow mask evaporation, provided that the device parameters (U and R_N) are appropriately chosen.

The calibration of the electron thermometer is shown in Fig. 2, where the temperature dependence of the voltage V_{th} across the thermometer junction, for bias currents of 0.24 and 0.43 nA, and when the electron refrigerator was not operating is plotted. Since very little power is dissipated in the normal metal strip, we make the assumption that the electron temperature is equal to the temperature of the dilution refrigerator T_p. The squares are the measured data and the solid curves are the calculated values from Eq. (1) using R_N = 8 kΩ and Δ/e = 190 μV. The fit is good for temperatures above 100 mK, but does not agree with the measurements at lower temperatures. From independent measurements we conclude that a smeared energy gap, due to the overlap between the normal metal electrode and the graded edges of the superconducting electrode, is the cause of the low temperature discrepancy between the data and Eq. (1). The data for the refrigerator junction, for which the overlap area was smaller, showed good agreement to 65 mK. Furthermore, we have found that the agreement with theory can extend down to 35 mK for tunnel junctions with no such overlap.

In Fig. 3 (a) we show the measured dependence of the voltage V_{th} across the thermometer junction versus the voltage V_{ref} across the refrigerator junction for lattice temperatures T_p of 100, 150, and 200 mK. The electron temperature, which was interpolated from Fig. 2 is indicated on the right axis. For bias voltages much smaller than Δ/e, the electron temperature remains constant since very little current flows through the refrigerator. When V_{ref} approaches Δ/e, V_{th} increases, indicating that the electron temperature has been reduced below that of the lattice. For higher voltages, the refrigerator junction dissipates energy in the normal electrode and thus increases the electron temperature. For our refrigerator the cooling power at 100 mK is about 7 fW, which gives a temperature drop of about 15 mK for the electrons. The solid lines in Fig. 3 (a) are the theoretical predictions using the measured parameters R_N = 10 kΩ, U = 0.5 μm^3, and fitted parameters Δ/e = 210 μV and $\sum$ = 4 $nWK^{-5}\mu m^{-3}$.

Though the theory is in excellent agreement with the data for T_p > 100 mK, there are deviations at lower temperatures. In Fig. 3 (b) we expand the V_{th} versus V_{ref} data for phonon temperatures of 40 and 100 mK. The dashed horizontal line corresponds to the voltage V_o at which the measured thermometer calibration in Fig. 2 linearly extrapolates to 0 K. The thermometer voltage exceeds V_o for T_p = 40 mK and V_{ref} > 157 μV, indicating that the simple theory can no longer explain the data. This observation may be explained by the fact that the concept of an electron temperature is no longer valid in this regime. The reason for this is that energy is extracted from the electrons at a rate $\tau_{nis}^{-1} \approx (dP_{max}/dT)C^{-1} \approx 10^5$ s^{-1}, where C is the heat capacity of the strip, whereas the electron-electron relaxation rate is $\tau_{e\text{-}e}^{-1} \approx 5\text{x}10^6 T$ s^{-1} with T in units of Kelvin.[11] Below about 20 mK, $\tau_{nis}^{-1} > \tau_{e\text{-}e}^{-1}$. Since the electron-electron interaction is responsible for thermalizing electrons at these temperatures, a non-equilibrium energy distribution is induced where the electron population is significantly depleted above E_F. Thus, in order to maintain a constant current through the thermometer junction, V_{th} has to increase above V_o. This observation suggests that the NIS tunnel junction might be a useful tool for creating and probing non-equilibrium distributions in normal metals.[5]

In conclusion, we have demonstrated that the unique thermal transport properties of the NIS junction can be exploited to manipulate the Fermi-Dirac distribution in the normal electrode and to significantly cool the electrons below the lattice temperature. At the lowest temperatures we find that the electron energies depart strongly from an equilibrium distribution. This novel refrigeration technology may also be used to cool both electrons and phonons in a thermally isolated substrate, such as a thin low-thermal-conductivity membrane. This type of refrigerator would be useful for cooling devices which dissipate very low power, such as x-ray or infrared detectors. We calculate that it should be possible to cool a membrane to below 100 mK from a temperature of 300 mK within 0.1 s,[12] thus providing an alternative to more complex dilution or adiabatic demagnetization refrigerators in certain applications.

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References

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

2. F. C. Wellstood, C. Urbina, and J. Clarke, IEEE Trans. Magn. **MAG-25**, 1001 (1989).

3. M. Nahum and J. M. Martinis, Appl. Phys. Lett. **63**, 3075 (1993).

4. A related refrigeration scheme where a two-dimensional electron gas would be cooled below the bulk temperature has been recently proposed; see H. L. Edwards, Q. Niu, and A. L. de Lozanne, Appl. Phys. Lett. **63**, 1815 (1993). Our measured system however, allows electrons in large metallic films to be cooled, is simple to fabricate, and may enable the cooling of both electrons and phonons in bulk samples.

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

6. L. Solymar, *Superconductive Tunnelling and Applications* (Wiley, New York, 1972).

7. For simplicity we discuss the case where eV>0. The results are also valid for eV<0, except that here the tunneling is due to holes.

8. R. L . Kautz, G. Zimmerli, and John M. Martinis, J. Appl. Phys. **73**, 1 (1993).

9. A. F. Andreev, Sov. Phys. JETP **19**, 1228 (1964).

10. T. A. Fulton and G. J. Dolan, Phys. Rev. Lett. **59**, 109 (1987).

11. P. Santhanam and D. E. Prober, Phys. Rev. B **29**, 3733 (1984).

12. Here we assume a 0.5 µm thick silicon nitride membrane with an area of 2x2 cm^2, a tunnel junction with R_N=0.1 Ω, and a normal metal electrode with an area of 1x1 cm^2 and a thickness of 100 nm. The thermal conductivity of the membrane is taken as $\kappa = 162T^{5/2}$ $\mu Wcm^{-1}K^{-1}$ (W. Holmes, private communication). We also assume that none of the power P_S leaks back into the normal electrode, a condition which may be difficult to achieve in practice.

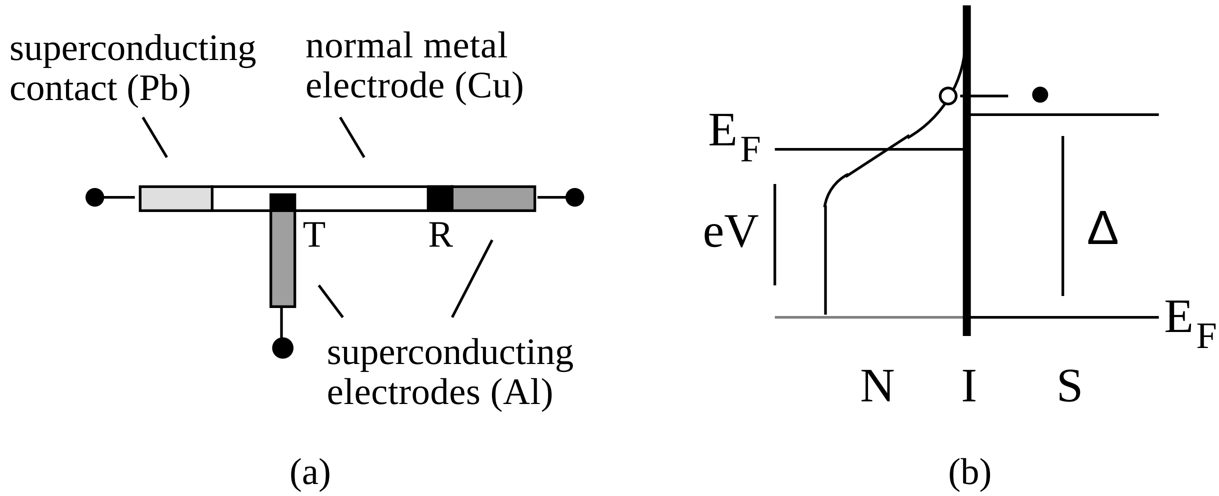


Figure 1. (a) Schematic of the electron refrigerator. The thermometer and refrigerator tunnel junctions, labeled T and R, are depicted as black squares. (b) Energy level diagram for the refrigerator junction. The junction is biased close to the superconducting gap Δ, so that only electrons whose energy is higher than E_F tunnel out of the normal electrode.

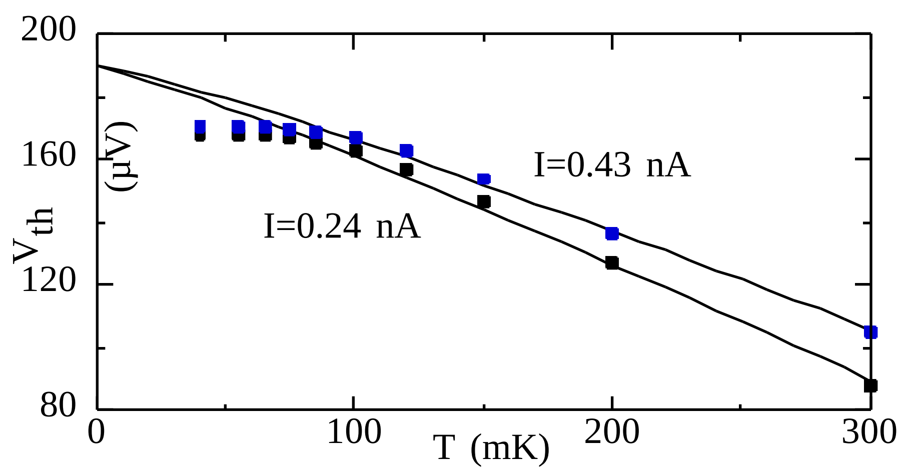
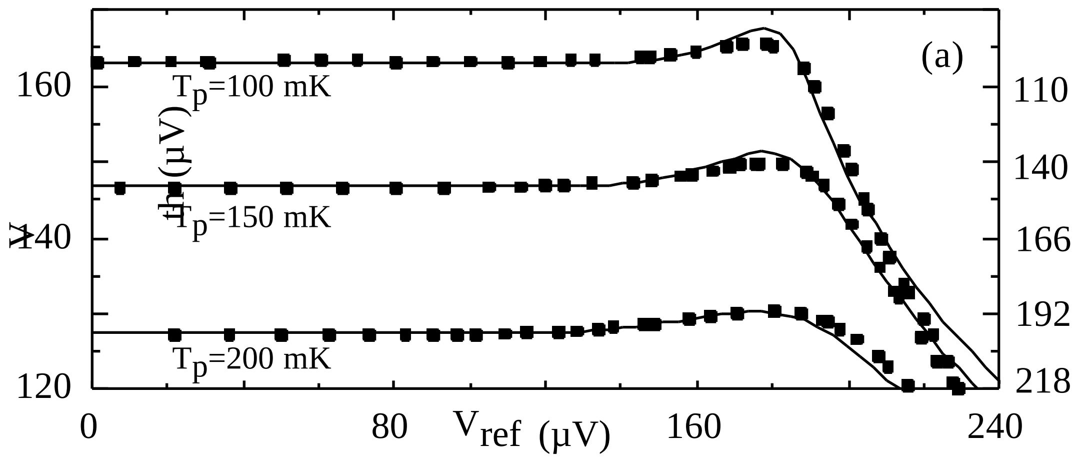


Figure 2. Temperature dependence of the voltage V_{th} across the thermometer junction for bias currents of 0.24 and 0.43 nA. The squares are the measured values and the solid lines are calculated using Eq. (1) and R_N = 10 kΩ and Δ/e = 190 μV.



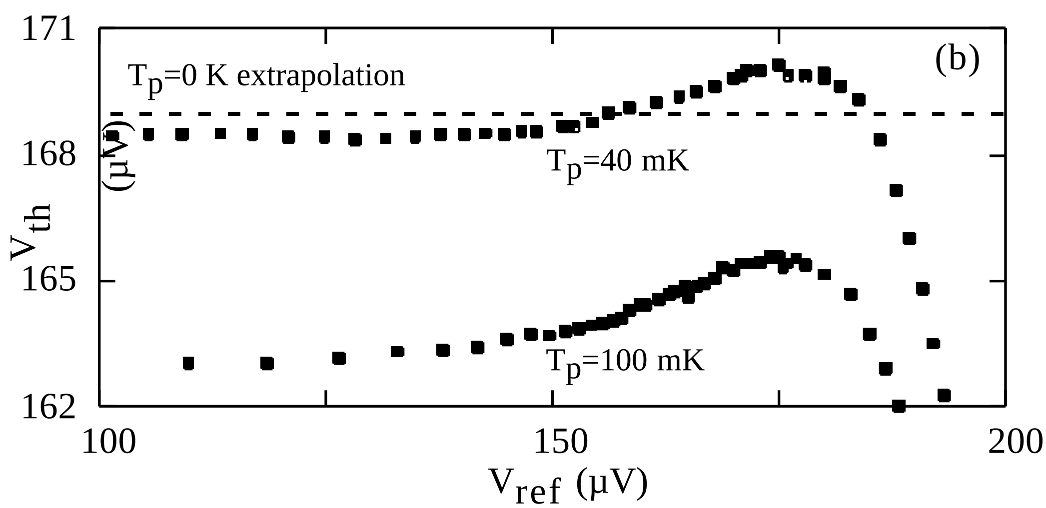


Figure 3. (a) Dependence of the thermometer voltage V_{th} on the voltage V_{ref} across the refrigerator junction for lattice temperatures of 100, 150, and 200 mK, and for a bias of 0.24 nA through the refrigerator junction. The squares are the measured values and the solid lines are the theoretical predictions using the measured parameters R_N = 10 kΩ, U = 0.5 μm^3, and fitted parameters Δ/e = 210 μV and ∑ = 4 nWK^{-5}μm^{-3}. The increase in the thermometer voltage for $V_{ref} \approx 180$ μV indicates that the electrons are cooled below the

lattice. The electron temperature, which was interpolated from Fig. 2, is indicated on the right axis. (b) Dependence of the thermometer voltage on the voltage across the refrigerator junction for lattice temperatures of 40 and100 mK. The dashed horizontal line is the voltage at which the temperature extrapolates to 0 K.