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Quasiparticle Behavior in Tunnel Junction Refrigerators

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Abstract
We present simulations of quasiparticle creation, propagation, and loss in the superconducting electrode of a normal-insulator-superconductor tunnel junction refrigerator. We calculate the electronic temperature in the superconducting electrode from self-consistent solutions to the diffusion equation. We then calculate the power load on the normal electrode due to recombination phonons and the reduction in cooling power due to the elevated temperature of the superconductor. Our calculations explain the degraded cooling performance observed in 15-20 μm sized Ag/AlOx/Al junctions.

Keywords
microrefrigeration, quasiparticles, tunnel junctions

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Since the first demonstration of electron cooling by normal-insulator-superconductor (NIS) tunnel junctions [1], there has been growing interest in the development of on-chip refrigerators having base temperatures near 100 mK when operated from bath temperatures of several hundred mK. [2,3] In this paper, we show how heating of the electron system in the superconducting electrode of a NIS junction can degrade refrigerator performance.

Current flow through a NIS tunnel junction heats the electron system in the superconducting electrode through the creation of quasiparticles. This heating degrades the cooling performance of the junction through two mechanisms. First, the annihilation of quasiparticles produces phonons which can travel through the tunnel barrier and excite electrons in the normal electrode. Second, the power removed from the normal electrode decreases as the quasiparticle density in the superconductor increases. Electrons which tunnel from below the Fermi level of the normal metal and annihilate hole-like excitations in the superconductor are especially detrimental to the cooling power of the junction. The two degradation mechanisms are described quantitatively below.

If the quasiparticle density in the superconducting electrode of the junction is $n_x + n_{th}$ where n_{th} is the thermal density, then the recombination rate is $\Gamma_R (n_x + n_{th})^2 V_S$ quasiparticles per second where Γ_R is the effective recombination rate per unit density and V_S is the electrode volume. The power load on the normal electrode due to recombination phonons is then given approximately by

$$\Gamma_R (n_x{}^2 + 2 n_x n_{th}) V_S \, \Delta \, p_{p-e} \tag{1}$$

where Δ is the energy gap and p_{p-e} is the probability that a recombination phonon excites an electron in the normal electrode.

The power deposited in the superconducting electrode of a NIS junction is given by

$$P_S = \frac{1}{e^2 R_N} \int_{\Delta}^{\infty} E N(E)[f_N(E+eV_b) + f_N(E-eV_b) - 2f_S(E)]dE \quad (2)$$

where R_N is the normal state resistance, $N(E)$ is the energy-dependence of the density of states, V_b is the bias voltage, and f_N (f_S) is the Fermi function in the normal (superconducting) electrode. We assume that the electron system in the normal metal (superconductor) has an effective temperature T_N (T_S). The cooling power in the normal electrode, P_N, is $P_S - IV_b$. In Fig. 1, we plot the normalized cooling power as a function of T_S / T_N for T_N equal to 0.1, 0.2, and 0.3 K and Δ=180 μeV. It can be seen that the cooling power decreases when T_S exceeds T_N. The loss in cooling power due to heating in the superconductor is given by

$$P_N(T_N, T_S) - P_N(T_N, T_S = T_b) \quad (3)$$

where T_b is the bath temperature.

Previous experimental work on 15-20 μm long junctions described deviations from the expected thermal behavior in terms of a power load on the normal electrode $\beta P_S(T_N, T_S = T_b)$. [3] This description implies that a fraction β of the power deposited in the superconductor, P_S, returns to the normal electrode. The fraction β was measured to be 0.125-0.15 for T_b between 0.2 and 0.3 K and V_b between 0 and $1.1\Delta / e$. The same β was found for 2 junctions with lengths of 20 and 15 μm, areas of 400 and 150 μm^2, and specific resistances of 3300 $\Omega\mu m^2$ and 7200 $\Omega\mu m^2$, respectively. We next describe how to calculate β.

To estimate the power load due to quasiparticle recombination and the loss in cooling power due to values of $T_S > T_b$, we calculate the quasiparticle density in the superconducting electrode. This is equivalent to calculating T_S. The spatially varying excess quasiparticle density, $n_x(x)$, is given by

$$D\nabla^2 n_x - \Gamma_R(n_x{}^2 + 2n_x n_{th}) + \Gamma_{QP} g(x) = 0 \qquad (4)$$

where D is the diffusion constant. The end of the junction is a mirror and the point where the superconducting lead overlaps a normal contact pad is a sink. The function $g(x)$ is zero except under the junction where $g(x)^{-1}$ is the volume of the superconducting electrode. The rate of quasiparticle injection, Γ_{QP}, is given by Eq. (2) without the factor of E inside the integral. Since Γ_{QP} is an integral function of T_S and thus n_x, we solve Eq. (4) iteratively until a self-consistent solution for n_x is found.

Calculated values of n_x due to currents of 1.67 μA (solid line) and 6.84 μA (dashed line) are plotted in Fig. 2. These currents correspond to V_b= $0.75\,\Delta/e$ and $1.0\,\Delta/e$, and T_N= 0.3022 and 0.3086 K, respectively. The bath temperature was 0.304 K. The injection region extends from x=0 to x=20 μm and the quasiparticle sink occurs at x=47.5 μm. The cross-sectional area is 3.4 μm^2. Including phonon trapping, we calculate Γ_R=30 μm^3/s. The diffusion constant D is calculated from resistivity measurements and the quasiparticle dispersion relation. A value for D of 9×10^9 μm^2/s is typical, but there is a weak dependence on V_b, T_N, and T_S. To simplify, we set T_S equal to T_b when calculating D. The excess densities of 10,500 μm^{-3} and 37,300 μm^{-3} in the junction region correspond to T_S= 0.371 and 0.447 K, respectively.

Given n_x and T_S in the superconducting electrode of the junction, it is simple to calculate β. Using the phonon-electron interaction rate for 2Δ phonons in Ag and the phonon escape rate from the Ag normal electrode, we estimate that p_{p-e} in Eq. (1) is approximately 0.4. We conclude from Eq. (1) that for I=1.67 μA, recombination produces a power load of 4 pW on the normal electrode. The decrease in cooling power due to elevation of T_S is also significant. From Eq. (3), we conclude that the elevation of T_S above T_b reduces the cooling power by 11 pW. Summing these powers and dividing by Eq. (2) evaluated with $T_S = T_b$, we arrive at β=.05. For I=6.84 μA, the recombination load is 37 pW, the decrease in cooling power is 42 pW, and β is .06. These predictions for β incorporate no free parameters and agree with measurement to factors of 2-3. The predictions are largely independent of bias, in good agreement with measurement. Similar calculations carried out at T_b=0.226 K yield β=.05 for V_b=0.75 Δ / e and β=.06 for V_b=0.9 Δ / e. Hence, the predicted values of β are independent of T_b over the range 0.2-0.3 K, also in good agreement with measurement. The predicted values of β can be increased to 0.125-0.15 by decreasing the mean free path by a factor near 3.

The predicted values of β for the 15 μm long junction in [3] are smaller: .02-.03. It is surprising that β measured in the 15 μm and 20 μm junctions is the same because of the higher specific resistance and shorter distance quasiparticles need diffuse before leaving the smaller junction. It is possible that the mean free path in the Al of the smaller junction is shorter than in the larger because shadow mask deposition produces more disorder in small features.

In conclusion, we have demonstrated techniques for calculating the degradation in NIS refrigerator performance caused by heating of the superconducting electrode. Our calculations are in close quantitative agreement with measurements and show the same insensitivity to bath temperature and bias voltage.

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Fig. 1. Cooling power P_N with normal electrode temperature T_N and superconducting electrode temperature T_S plotted as a function of T_S / T_N for T_N=0.1, 0.2, and 0.3 K. The result is normalized by P_N evaluated with T_S=T_N. The bias is 0.95 Δ / e.

Fig. 2. Excess quasiparticle density $n_x(x)$ plotted versus x for junction currents of 1.67 μA and 6.84 μA.

Fig. 1.

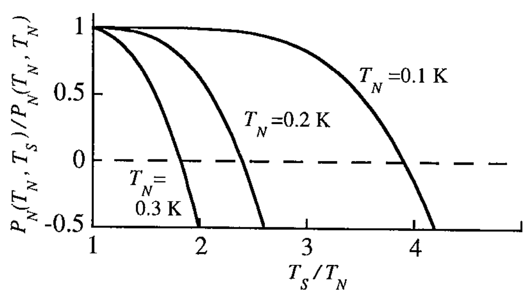

Fig. 2.