Nonequilibrium Superconductor-Normal Metal Tunnel Contact and the Phonon Deficit Effect

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We consider tunnel microrefrigerators at low temperature. There is a number of experimental studies performed on microrefrigeration in tunneling superconductor–normal metal (SN) structures. Related to these experiments, only the electron subsystem has been considered theoretically. Independently, the phonon deficit effect has been studied a while ago in superconductor-superconductor tunnel junctions. It can be regarded as a possible prototype scheme for superconducting microrefrigerators. We try to provide the missing link between experiments on the SN tunnel junction refrigerators and the theory which includes microscopically phonons in combination with the mechanism of the phonon deficit effect.

A normal metal–superconductor tunnel contact can be used to cool the normal metal electrode and a membrane linked to it \cite{1}. Many groups have investigated SN tunnel contact as the prototype for the tunnel contact microrefrigerator or electronic refrigeration \cite{2} device on a chip. All electron subsystem cooling experiments are based on Parmenter’s idea \cite{3} (or equivalently the Peltier effect for non–superconducting case) to find a method of extracting the normal electrons, thermally excited from the gap edge region, into one of the superconducting electrodes in a superconductor–superconductor (SS\textsuperscript{prime}) tunnel contact. The SN contact used in these experiments can be considered as the limiting case of an SS\textsuperscript{prime} tunnel contact.

The phonon “deficit effect” was initially predicted as an effect accompanying the enhancement of superconductivity in a high–frequency electromagnetic field \cite{4}. It has widely been studied \cite{5} for a variety of different situations including refrigeration in the SS\textsuperscript{prime} contacts. Here we will consider the behavior of an SN tunnel contact as a limiting case of an asymmetrical SS\textsuperscript{prime} tunnel contact.

As in \cite{5} we consider a massive superconductor (S\textsubscript{2}) with the BSC gap $\Delta_2$ and the critical temperature $T_{c_2}$ linked to a thin normal metal (N) or superconducting film with thickness $d \sim \xi_0 \sim v_F/T$ by means of an oxide layer (here $v_F$ is the particle velocity at the Fermi level, $\xi_0$ is the coherence length). This system is linked to a thermostat at a temperature $T$. The electron and hole distribution functions in the massive superconductor are those at equilibrium due to rapid diffusion reabsorption of the tunneling excitations. The distribution of electrons ($n_+$) and holes ($n_-$) in the thin film ($S$ or $N$) is described by the kinetic equation

$$ u_\epsilon \frac{\partial n_{\pm \epsilon}}{\partial t} = Q(n_{\pm \epsilon}) + J(n_{\pm \epsilon}, N_\omega). $$

(1)

The explicit form of the tunnel source and electron–phonon collision integral operators are given in \cite{5}, $u_\epsilon = |\epsilon| \theta(\epsilon^2 - \Delta^2)/\sqrt{\epsilon^2 - \Delta^2}$ is the BCS density of states, $\epsilon$ is the electron energy. Because the smallness of the film (S or N) thickness $d$ we assume that the phonons have a sufficient time to leave the film and they do not back influence on the electrons in this thin film. At this condition we take $N_\omega = N_\omega^0$ ($N_\omega^0$ is the Bose distribution function for phonons) for $J(n_+, n_-)$ in equation (1) as in \cite{5}. If the system is in the stationary state then we can solve by iterations the equation (1) and find stationary state solutions for particle and hole distribution functions. The intensity of the phonon radiation at a frequency $\omega_q$ in a range $d\omega_q$ is equal to

$$ \frac{d\hat{P}_{\omega_q}}{d\omega_q} \propto \frac{v\lambda\omega_D\omega_q^3}{16\pi\epsilon_F u^3} I(N_{\omega_q}^0), $$

(2)

where $v$ is the volume of the film, $\omega_D$, $\lambda$, $u$, $\epsilon_F$ are the Debye frequency, the dimensionless electron–phonon interaction constant, the sound velocity and the Fermi energy, respectively. $I(N_{\omega_q}^0)$ is the phonon–electron collision operator. There are negative and positive phonon fluxes \cite{5} between the thin film and the thermal reservoir. The net phonon flux under certain conditions can be either negative or positive.

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FIG. 1. Phonon absorption curves for different temperatures. \( P_0 = v\lambda\omega D T_c^3 \sqrt{(16\pi\varepsilon_F u^4)} \). \( T_{C_0} = 1\text{K} \), \( T_{C_1} = 0.2\text{K} \), \( \Delta_2(T)/T_{C_2} = 1.759 \) and \( \Delta_1(T)/T_{C_2} \) is equal to 0.34, 0.29, 0.19 and 0.04 from top to bottom of insert respectively.

Fig. 1 illustrates the results of our numerical simulation for the phonon emission (absorption) at different voltages \( V \) for the \( SS' \) tunnel contact. We can see that at low temperatures cooling capacity of the asymmetric \( SS' \) contact is low and as \( \Delta_1 \) goes to zero its cooling capacity is increased. Above the temperature \( T > T_{C_1} \) the cooling capacity of the tunnel contact decreases. This means that the BCS peculiarities in the electrons density of states plays a very important role for the cooling process. In the case of the normal metal this picture changes so that there will be almost only phonon absorption from the heat–bath at low temperatures and phonon emission to the heat–bath at higher temperatures. From the above analysis it is clear how to optimize the parameters of the \( SS' \) \( SN \) tunnel contact to get suitable device for low temperature microrefrigeration.

This work has been supported by NSERC Canada. G. M. is grateful to the "Programme québécois de bourses d’excellence" of Québec for the financial support.

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