Ultra-efficient Cooling in Ferromagnet-Superconductor Microrefrigerators

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Abstract

A promising scheme for electron microrefrigeration based on ferromagnet-superconductor contacts is presented. In this setup, cooling power densities up to \(600 \text{nW/µm}^2\) can be achieved leading to electronic temperature reductions largely exceeding those obtained with existing superconductor-normal metal tunnel contacts. Half-metallic \(\text{CrO}_2/\text{Al}\) bilayers are indicated as ideal candidates for the implementation of the device.

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Heat transport through metal-superconductor interfaces can be applied to microcooling [1–3]. The physical mechanism underlying this electronic cooling is quite simple. When a normal metal (N) is brought in contact with a superconductor (S), quasi-particle transport is effective only at energies larger than the S gap ($E > \Delta$). In fact, owing to the existence of the gap in the energy spectrum of the superconductor, at a given bias across the SN system only electrons possessing energies higher than the gap match available single-particle states and can transfer into the S portion of the junction (see Fig. 1(a)). This selective transfer of "hot" carriers leads to the lowering of the effective electron temperature of the N electrode, even in the regime when electrons are thermally decoupled from the lattice. This situation can be experimentally realized with SN tunnel junctions where transport is dominated by quasi-particle dynamics. This unique property of Superconductor-Insulator-Normal metal (SIN) contacts was successfully employed for the realization of microcoolers [1,2]. Intrinsically, however, SIN devices present large values of the contact resistance ($R_n$) which hinder carrier transfer and lead to a severe limitation in the achievable cooling powers [2].

Decreasing $R_n$ by using high-transparency interfaces is not a viable route to increase cooling power. In this case, in fact, another process dominates carrier transfer across the junction. At low $R_n$ values, carrier transfer is made possible by Andreev reflection (AR) even at energies $E < \Delta$ [3]. In AR electrons may coherently evolve into holes that retrace the incoming electron time-reversed path and transfer a Cooper pair in S (see Fig. 1(b)). This does lead to increased conductivity, but does not contribute to thermal transport through the system. In practical devices a compromise must be reached and an optimal transparency value can be determined for a given microrefrigerator structure [3].

In this Letter we propose a cooling mechanism alternative to traditional SIN junctions which will be shown to be highly efficient. Our proposal is based on the use of a thin ferromagnetic layer (F) in good electric contact with S as shown in Fig. 1(c). The physical basis of the FS microcooler operation resides in the spin-band splitting characteristic of F. In fact the electron ($e$) involved in AR and its phase-matched hole ($h$) must belong to opposite spin bands (Fig. 1(d)); thus, suppression of the Andreev current [3] occurs in an FS junction.
and its intensity depends on the degree of the F-layer spin polarization $P$. In the limit of large $P$ and good metallic contact between the F and S electrodes, we observe a drastic suppression of the subgap current, while keeping efficient hot-carrier transfer leading to a considerable thermal flux $J$. Cooling power densities are almost two orders of magnitude larger than those of optimized SIN junctions. This efficiency enhancement translates in a dramatic reduction of the final achievable electron temperature.

The device is sketched in Fig. 1(c). It consists of a NFS microcooler biased at a voltage $V$. Since the refrigeration stems from the FS portion, we shall focus on this junction only. Let us consider a ballistic FS contact with a perfectly transparent interface [7]. In such a junction the overall cooling power $J$ is equal to the sum of terms of the form [5]

$$\frac{1}{\hbar} \int d\mathcal{E} \left\{ \mathcal{E} [1 - B - A] - eV [1 - B + A] \right\} (f_F - f_S) \quad (1)$$

each relative to a given angle of incidence and spin species. In (1), $f_{F,S}(\mathcal{E})$ is the electron Fermi distribution function in F(S), whereas $A(\mathcal{E})$ and $B(\mathcal{E})$ are the Andreev and normal reflection probabilities obtained, in close analogy to Refs. [6,8], as solutions of the Bogoliubov-de Gennes equations. The S pairing potential is approximated as a step-function [8], while F is described with the usual Stoner model [6]. Differences in the effective-mass and Fermi-velocity values between F and S are neglected. Note that $J$ is a function of spin polarization (via the scattering probabilities), bias voltage and temperature.

In order to evaluate the final electron temperature we need to consider also the mechanisms that can transfer energy into the ferromagnet. The main contribution is due to electron-phonon coupling and is given by [9,10] $J_l = \Sigma V (T_e^5 - T_l^5)$, where $V$ is the volume of the F electrode, $T_{e(l)}$ is the electron (lattice) temperature and $\Sigma$ is a material-dependent parameter of the order $10^{-9}$ WK$^{-5}$ $\mu$m$^{-3}$. For our purposes we can neglect the power dissipated in the resistance of the F layer [1,2]. The final electron temperature $T_e$ is determined by the energy-balance equation $J(P, V, T_e, T_l) + J_l(T_e, T_l) = 0$. In writing this expression we set the superconductor temperature equal to the bath temperature $T_l$. Note that this is an idealized assumption since the presence of hot quasi-particles in S, that may strongly
decrease the real cooling capability of the device, is expected. In real applications, however, one can overcome this problem through the exploitation of “quasi-particle traps” attached to the superconductor itself as described in Ref. [3].

Figure 2(a) shows $T_e$ as a function of bias for two starting lattice temperatures (i.e., the system temperatures at $V = 0$) $T_l = 200$ mK (solid lines) and $T_l = 300$ mK (dotted lines). The calculation was performed for half-metallic ($P = 1$) FS (thick lines) and for SIN (thin lines) microcoolers, assuming Al as superconductor ($\Delta_{Al} = 180$ µeV). Other junction parameters were taken according to experimental values [1,2,11]. In particular for the SIN-junction specific contact resistance we assumed a value $0.4 \Omega \mu m^2$, corresponding to very high-quality Cu/Al$_2$O$_3$/Al junctions [1,2]. Figure 2(a) shows the remarkable $T_e$ reduction provided by the FS cooler with respect to the NIS cooler. What shown in Fig. 2(a) is not meant to be a comparison with the best optimized SIN cooler (i.e., a SINIS refrigerator) [2], however it helps in establishing the main differences between the single FS cooling element and the single SIN one. Even starting from 200 mK, for which the tunnel junction provides its largest cooling effect (a temperature reduction of about 10% at $eV \approx \Delta$), the FS cooler yields $T_e$ of the order of 10 mK (a temperature reduction of about 95%). This marked difference stems from the high contact resistance of the SIN junction that strongly affects its performance and must be compared to specific contact resistances as low as $10^{-3} \Omega \mu m^2$ that are currently achieved in highly transmissive FS junctions [12]. For $eV < \Delta$, the FS-junction cooling power is large and, contrary to the SIN device, not localized only at $eV \approx \Delta$. For $eV > \Delta$, instead, the increase in the electron temperature is quite rapid owing to the high current driven through the FS contact.

The large cooling-power surface density $J_A$ makes the FS microrefrigerator a high performance device. Figure 2(b) shows $J_A(P)$ calculated at each optimal bias voltage, for some values of the lattice temperature. In the inset, the same quantity is plotted for a SIN junction versus interface transmission probability $D$ [3]. The comparison shows that for $P = 1$ at $T \approx 0.4 \Delta/k_B$ it is possible to achieve power densities up to 600 nW/µm$^2$, i.e. 30 times larger than those for the SIN junction at the optimized transmissivity ($D \approx 3 \times 10^{-2}$ at
\[ T \simeq 0.3 \Delta/k_B \). In real applications, however, SIN interface transmissivity is much smaller \((\mathcal{D} \approx 10^{-6} \div 10^{-5})\), limiting the achievable cooling power density to some pW/\(\mu\text{m}^2\).

The proposed cooling mechanism is robust against various possible sources that can lower quasi-particle transmission or enhance AR. We have evaluated the impact of incomplete polarization of the ferromagnet \((\mathcal{P} < 1)\), of low transmittance FS contacts and of spin-flip processes. Figure 3 shows the calculated dimensionless cooling power \(\mathcal{J}(V)\) for some \(\mathcal{P}\) values at \(T = 0.4 \Delta/k_B\). For each value of polarization there exists an optimal bias voltage which maximizes \(\mathcal{J}\). For \(\mathcal{P} = 1\), \(\mathcal{J}(V)\) is maximized around \(V \simeq \Delta/e\). Notably, even for \(\mathcal{P} = 94\%\) there still is a positive heat current. The inset of Fig. 3 shows \(\mathcal{J}(T)\) calculated at the optimum bias voltage for some values of \(\mathcal{P}\). The heat current is maximum for \(T \simeq 0.4 \Delta/k_B\).

In addition, lowering \(\mathcal{P}\) leads to a reduction of the useful temperature window for electron cooling. The same behavior was verified in the presence of spin-flip scattering events. We calculated this by allowing a random misalignment of magnetic moments within a given angle from the perfect alignment, which produces a decrease in the current polarization. (There is, however, no evidence that such processes occur in CrO\(_2\)/S nano-junctions which are the system we suggest for the implementation of the FS microcooler.) An important figure of merit of the refrigerator is represented by its coefficient of performance (COP), which is the ratio between the cooling power and the total input power. Our calculations show that for \(\mathcal{P} = 1\) in the 0.2 \(\div\) 0.4 \(\Delta/k_B\) temperature range the COP, evaluated at the optimum bias voltage, exceeds 20\% reaching its highest value (23\%) at about \(T \simeq 0.3 \Delta/k_B\). For \(\mathcal{P} = 96\%\) we obtain about 10\% efficiency at the same temperature.

In order to simulate a non-perfectly transparent FS contact caused by fabrication procedures or mismatch in material parameters [13], we have inserted an insulating barrier at the interface. The numerical simulation reveals that for \(\mathcal{P} = 1\) and low transmittance interface (e.g., \(\mathcal{D} = 0.1\)), the variation in the final electron temperature is not appreciable.

The FS junction discussed so far is part of the NFS device of Fig. 1(c). We estimated the impact of the F-layer thickness on the NFS-device cooling power. We verified that cooling effects comparable to the FS case can be reached for thickness values of the order of a few
nm (i.e. corresponding to the magnetic length $\hbar v_F/h_0$, $h_0$ being the F exchange field and $v_F$ the Fermi velocity).

In conclusion we should like to indicate half-metallic CrO$_2$ (chromium dioxide) [14,15] in combination with Al as the ideal candidate for the implementation of these devices. The well-developed CrO$_2$ technology [16] can in fact be used to realize complex FS arrays coupled with normal electrodes for optimal device geometries.

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\[ \Sigma = 2 \times 10^{-9} \, \text{WK}^{-5} \mu \text{m}^{-3} \] (typical of Cu), and \( R_{nFS} = 28 \, \text{m\Omega} \) (assuming a Fermi energy \( E_F = 5 \, \text{eV} \)).

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FIGURES

FIG. 1. (a) Biasing the SIN junction around the energy gap $\Delta$ allows more energetic electrons $e$ to tunnel into S, thus cooling the N electron population (see text). (b) Schematic description of Andreev reflection at a NS contact. (c) Scheme of the proposed NFS microrefrigerator. The NF junction is supposed to be a highly transmissive electric contact. (d) Schematic representation of the principle of operation of the NFS microcooler. For $P = 1$, AR is hindered by the absence of available states for reflected holes, $h$. This subgap electron-transport suppression mechanism allows the operation of the microrefrigerator in the presence of efficient carrier transfer to S.

FIG. 2. (a) Electron temperature $T_e$ versus bias voltage for a half-metallic ($P = 1$) FS (thick lines) and a SIN (thin lines) microcoolers for two starting bath temperatures $T_i$ at $V = 0$: 300 mK (dotted curves) and 200 mK (solid lines). (b) Maximum cooling-power surface density $J_A$ versus spin polarization $P$ for various temperatures. The inset shows the same quantity for a SIN junction as a function of contact transmissivity $D$.

FIG. 3. Dimensionless cooling power $J$ of a FS contact versus bias voltage at $T = 0.4 \Delta/k_B$ for several $P$ values. The inset shows the heat current calculated at the optimal bias voltage versus temperature for some $P$ values.
Fig. 1
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Fig. 2
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Fig. 3

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\[ T = 0.4 \frac{\Delta}{k_B} \]

\[ \mathcal{J} / (\Delta^2 / e^2 R_n) \times 10^{-2} \]

\[ eV/\Delta \]

\[ k_B T/\Delta \]