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Phonon-blocked junction refrigerators for cryogenic quantum devices

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Abstract—Refrigeration is an important enabler for quantum technology. The very low energy of the fundamental excitations typically utilized in quantum technology devices and systems requires temperature well below 1 K. Expensive cryocontainers are utilized in reaching sub-1 K regime and solid-state cooling solutions would revolutionize the field. New electronic microcoolers based on phonon-blocked semiconductor-superconductor junctions could provide a viable route to such miniaturization. Here, we investigate the performance limits of these junction refrigerators.

I. INTRODUCTION

Quantum devices are typically operated in massive and expensive cryoliquid-based refrigerators capable to reach sub-100 mK temperature. Typically these devices only require their miniaturized active elements to reach such low temperature. Compact solid-state cooling solutions could significantly decrease costs, complexity, maintenance and physical space required to reach low temperatures. Integrated on-chip electronic coolers and miniaturized cooled platforms [1,2] solutions would enable e.g. wider-spread and cost-effective refrigeration for quantum information processing [3,4], monolithic photon detection [5] and spaceborne detectors [6].

In Ref. [7] we demonstrated a promising novel approach for cooling at sub-kelvin temperatures: A semiconductor - superconductor (Sm-S) tunnel junction, where thermionic cooling arises from the voltage controlled evacuation of the hotter electrons through energy-gapped superconducting leads and acoustic phonon transmission bottleneck at the junction limits the parasitic phonon thermal conductance. The latter is the key innovation compared to previous works of superconducting tunnel junction coolers, where electron-phonon coupling in lateral cold fingers limits the operation [1].

The operation range of superconducting coolers scales with the critical temperature of the superconductor, T_c. In analogy with conventional thermoelectric coolers, it may be expanded by cascading stages with superconductors with different T_c by using the 3D configuration introduced in Ref. [7]. Such cascade is depicted also in Fig. 1(a). In this communication, we investigate the operation of single stages of Sm-S junction coolers in two cases: when the phonon blocking is enhanced with constrictions and when thermionic cooling power is increased with the transparency of the junction up to the limit defined by higher-order tunneling processes.

II. OPERATION PRINCIPLES AND MODELLING

Fig. 1(b) shows a conceptual image of a single phonon-blocked Sm-S tunnel junction cooling element. The operation principle is depicted in Figs. 1(c) and 1(d) with following four elements [7]: (i) weak electron-phonon coupling in the superconductor disconnects electron and phonon heat conduction channels, (ii) phonon branch heat transport is suppressed by thermal resistance R_{ph} (boundary resistance at the tunnel junction, R_{PTB} ), and thermal resistance of superconducting lead, R_{lead}, in series, (iii) electron heat channel is suppressed by the superconductor energy gap \Delta, and (iv) the electron cooling is enabled by quasiparticle filtering/thermonic tunneling by the same energy gap.

The cooling power is a function of tunnel junction resistance, R_{T}, and leakage in the energy gap, \gamma = R_{T}/R_{gap}, where \gamma is the (Dynes) leakage parameter and R_{gap} is the electric resistance of the junction at zero voltage [8]. A simplified equation for cooling power at optimal voltage bias \varepsilon_{opt} = (\Delta - 0.66k_{B}T)/e can be written as [7]

\[ P_{cool}(T_{N}) = \frac{\Delta^2}{e^2R_{T}} \cdot 0.59 \left( \frac{k_{B}T_{N}}{\Delta} \right)^{3/2} - \frac{1}{2} \frac{\varepsilon_{opt}^2}{\Delta^2}, \]

where e is the elementary charge, k_B is the Boltzmann constant and T_{N} is the temperature of semiconductor [9]. Equation (1) is valid when temperature is well below critical temperature.

The detrimental phonon heat leak through a thermal resistance (for example R_{PTB} or R_{lead}) can be described by

\[ P_{ph}(T_{N}, T_{0}) = \frac{1}{\alpha} (T_{N}^\beta - T_{0}^\beta). \]

It is related to thermal resistance as R(T) = \alpha T^{-n+1} when T_{N} = T_{0} = T. Here T_{0} is the temperature of the previous stage. Thermal resistance pre-factor \alpha and power n depend on the mechanism of the phonon transport. Temperature T_{N} in the simulations is determined by setting P_{ph} = P_{cool}.

For planar R_{PTB} and 3D R_{lead} n = 4 [10,8] and for ballistic 1D channel n = 2 [11]. In Ref. [7] an experimental value for R_{PTB} in a geometry similar to Fig. 2(a) was obtained and ballistic 1D case (thermal conductance quantum limit) was investigated theoretically. Here we model also diffusive quasi 1D case relevant for nanowire constrictions [Fig. 2(b)]. The heat transport in constrictions is estimated with the phonon Boltzmann transport equation (BTE) under the relaxation time approximation solved by the Discrete Ordinate Method
As the dominant phonon wavelength (at the temperatures of interest) is several orders of magnitudes larger than the Fermi wavelength, the phonon channel becomes one-dimensional earlier than electron channel when the later size is reduced [12]. This enables efficient heat removal by electrons while detrimental phonon thermal leaks are strongly suppressed. The upper limit of phonon thermal resistance is set by a one thermal conductance quantum divided by the transmission probability. 

\[ R_T = h/e^2 \] is the resistance quantum (\( h \) is Planck’s constant). In Ref. [15] an experimental value for the Andreev channel area was found: \( A_{ch} = 30 \text{nm}^2 \). This value was about ten times larger than the one that is predicted by theory.

The Andreev tunneling limit (based on Ref. [15] experimental results) is shown in Figs. 3(a) and 3(b) when the total phonon resistance is 220 K cm²/W, corresponding to a situation where the phonon flow is suppressed by constrictions in addition to the phonon thermal boundary resistance. The Figures can be used to identify the optimal operation range for highly-transparent tunnel junctions and guide fabrication efforts. Figs. 3(a) and 3(b) show that very good performance can be obtained even when Andreev reflection is taken into account.

**IV. Summary**

We have studied methods of enhancing the performance of phonon-blocked Sm-S tunnel junction coolers stages. Introduction of nanowire constrictions yields significant performance gain and extends the operation of the cooler to higher temperatures. Performance can be further enhanced by increasing the transparency of the tunnel junctions up to the point where higher order tunneling processes appear. As temperature difference larger than 50% per stage can be reached, our approach allows highly-attractive scalable and fully electronic refrigerator technology that can be used for quantum circuit applications in the 1 K - 100 mK temperature range with vanadium/aluminium stages. Even lower base temperature could be possible with a stage based on lower-gap superconductors such as titanium.

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Fig. 1. (a) Conceptual image of a cascaded cooler structure (top: cold, bottom: hot), (b) implementation of a cooling element in the cascade, and (c) electron and phonon heat fluxes in a tunnel junction. (d) Heat transfer equivalent circuit. Here $R_{\text{lead}}$ corresponds to the thermal resistance of the superconducting lead, $R_{\text{ph}}$ the thermal resistance of the junction and $R_{\text{ph}}$ the sum. (e), (f) Scanning electron micrographs of a cooler prototype studied in Ref. [8] to verify the phonon blocked operation. (f) Cross-section of a tunnel junction between the middle Si pillar and one superconducting Al lead. See also Ref. [8].
Fig. 2. (a)-(b) Different approaches for phonon filtering in superconductor: (a) Phonons are only filtered at the junction, and (b) nanowire constrictions are introduced. (c) Measurement data of Ref [8] (red dots). (c),(d) Simulations with tunnel junction with improved characteristic junction resistance, $R_J$, and leakage parameter, $\gamma$ (orange line), nanowire constrictions with two different typical boundary reflection specularity parameters, $p$ (blue lines) and constriction that is limited by 10 conductance quantum (cyan line). The data is shown as percentual cooling between the previous (hot) stage with temperature, $T_0$, and subsequent cold stage with temperature $T_N$. (e) Simulated cooling with traditional phonon thermal boundary resistance and lead resistance as a function of normalized temperature $T/T_c$, and product of electrical cooling and phonon blocking parameters (see (1) and (2)). Here $L_0$ is Lorenz number and $T_c$ critical temperature of the superconductor. (f) Simulated cooling when phonon channel is limited by limited number of thermal conductance quanta, $N$.

Fig. 3. Cooling at starting temperatures of 0.2 K and 0.3 K for aluminium when constrictions are introduced. Solid thick black line indicates the Andreev tunneling limit (see text).