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Proximity nanovalve with large phase-tunable thermal conductance

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We propose a phase-controlled heat-flux quantum valve based on the proximity effect driven by a superconducting quantum interference proximity transistor (SQUIPT). Its operation relies on the phase-dependent quasiparticle density of states in the Josephson weak-link of the SQUIPT which controls thermal transport across the device. In a realistic Al/Cu-based setup the structure can provide efficient control of thermal current inducing temperature swings exceeding $\sim$100 mK, and flux-to-temperature transfer coefficients up to $\sim$500 mK/$\Phi_0$ below 100 mK. The nanovalve performances improve by lowering the bath temperature, making the proposed structure a promising building-block for the implementation of coherent caloritronic devices operating below 1 K.

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Phase-dependent manipulation of heat in solid-state nanodevices is nowadays one of the major challenges of coherent caloritronics,1 and plays a key role in determining the physical properties of mesoscopic systems at low temperature. Toward this direction, the prototype for a heat interferometer has been recently realized with a superconducting quantum interference device (SQUID) where the modulation of the thermal current has been achieved thanks to the Josephson coupling.2–5 Yet, phase-dependent thermal transport has been also demonstrated in Andreev interferometers6–8 where the proximity effect in a normal metal affects its thermal conductance, and is controlled via a magnetic field.

Here we propose an alternative approach to control heat transport by envisioning a thermal nanovalve based on proximity effect but phase-controlled by a superconducting quantum interference proximity transistor (SQUIPT).9–12 Differing from SQUID-based and Andreev interferometers our device allows a drastic quenching of the thermal conductance which makes our proposal an efficient phase-tunable thermal nanovalve. Specifically, we expect an improvement of the temperature swing (up to $\sim$100 mK) and a flux-to-temperature transfer function exceeding 500 mK/$\Phi_0$ at 100 mK.

A sketch for the proximity nanovalve is shown in Fig. 1(a) and consists of a SQUIPT composed by a superconducting (S) ring interrupted by a diffusive normal metal (N) wire of length $L$. We assume the wire transverse dimensions to be negligible in comparison to its length so that it can be considered as quasi-one-dimensional. Superconducting correlations are induced in the N wire owing to proximity effect from the S loop which modifies the wire density of states (DoS).13 In addition, a normal metal (N1) or a superconducting electrode (S1) identical to S is tunnel-coupled to the middle of the wire through an insulating contact of negligible width respect to the wire length. $R_T$ denotes the normal-state resistance of the junction. We assume the SN ring and the N1(or S1) electrode to be in steady-state thermal equilibrium and to reside at different temperatures $T_L$ and $T_R$, respectively, with $T_L \geq T_R$. The nanovalve is therefore only temperature biased. In the limit of negligible geometric inductance of the ring it follows that $\varphi = 2\pi \Phi/\Phi_0$, where $\varphi$ is the phase difference across the SN boundaries, $\Phi$ is the applied magnetic flux through the loop, and $\Phi_0 = 2.067 \times 10^{-15}$ Wb is the flux quantum. The ring geometry allows to change $\varphi$ which leads to the modification of the N-wire DoS14 and, in turn, a drastic modification of thermal transport through the device.

The DoS in the N wire ($\mathcal{N}_{\text{wire}}$) is given by $\mathcal{N}_{\text{wire}}(\varepsilon,x) = |Re[g^R(\varepsilon,x)]|$, where $g^R$ is the normal retarded quasiclassical Green’s function, $\varepsilon$ is the energy, and $x$ is the spatial coordinate along the wire. The function $g^R$ can be obtained by solving the one-dimensional Usadel equation (we skip the supra index R)15

$$hD\ddot{g} + (\varepsilon + i\Gamma)[\tau_z,\dot{g}] = 0,$$  \hspace{1cm} (1)

where $D$ is the wire diffusion coefficient, the parameter $\Gamma$ accounts for the inelastic scattering rate within the relaxation time approximation,16–19 and $\tau_z$ is the third Pauli matrix in the Nambu space. The Green’s function $\tilde{g}$ is a matrix in this space with the form $\tilde{g} = g\tilde{z} + \tilde{f}$, being $\tilde{f}$ the anomalous Green’s function that is off-diagonal in Nambu space. The Usadel equation has to be complemented by the normalization condition $\tilde{g}^2 = 1$, where $\hat{1}$ is the unit matrix. The SN interfaces are modeled by proper boundary conditions. If the SN interfaces have large contact resistance $R_{SN}$ we use the Kupriyanov-Lukichev boundary conditions20 $\tilde{g}\partial_{\tilde{z}}\tilde{g}|_{\tilde{z}=\pm L/2} = \pm \frac{1}{2k_{\text{BL}}A}[g\tilde{z},\tilde{g}]$, where $A$ is cross sectional area of the SN interface, $\sigma$ the conductance of the N-wire and $g\tilde{z}$ are the Green’s functions of the left and right S electrodes defined as $g\tilde{z} = g\tau_3 + f_3[\cos(\varphi/2)i\tau_2 \pm \sin(\varphi/2)i\tau_1]$. Here,
$g_1(\epsilon) = \frac{e^{-i\epsilon + iT}}{\sqrt{(\epsilon + iT)^2 - \Delta^2}}$, $f_1(\epsilon) = \frac{\Delta}{\sqrt{(\epsilon + iT)^2 - \Delta^2}}$. $\Delta$ is the BCS temperature-dependent energy gap with critical temperature $T_c = (1.764k_B)^{-1}\Delta_0$, $\Delta_0$ is the zero-temperature order parameter and $k_B$ is the Boltzmann constant. Furthermore, we neglect the suppression of the ring order parameter at the SN interfaces due to inverse proximity effect. This latter can be made negligible by making the wire cross section much smaller than that of the S loop.\textsuperscript{9,21,22} If the SN contact resistance is negligibly small one imposes the continuity of the Green’s functions at the interface.

We first focus on the short junction limit (i.e., $E_{Th} = hD/L^2 \gg \Delta_0$, where $E_{Th}$ is the SNS junction Thouless energy). In this case the proximity effect can be maximized, and the performance of the nanovalue enhanced. This limit can be practically met with a copper N wire ($D = 0.01 \text{ m}^2/\text{s}$) of 100 nm length and an aluminum S ring ($\Delta_0 = 200 \mu\text{eV}$) for which $E_{Th} = 3.3 \Delta_0$. In such a case, the DoS in N can be obtained analytically.

$$N_{\text{wire}} = \text{Re} \left[ \frac{\epsilon - 2i\epsilon_0 g_s}{\left(\epsilon - 2i\epsilon_0 g_s\right)^2 + 2\epsilon_0 f_s \cos \left(\frac{\pi \Phi}{\Phi_0}\right)^2} \right], \quad (2)$$

where $\epsilon_0 = hD/(2LR_{SN}A\sigma) = \gamma E_{Th}$, and $\gamma$ is the transmissivity of the SN interface.\textsuperscript{23}

Figures 1(b) and 1(c) show $N_{\text{wire}}$ vs energy $\epsilon$ for different $\gamma$ values at $\Phi = 0$. A clear energy gap $\Delta_0$ in the DoS is visible even for quite low interface transmissivity (down to $\gamma \sim 0.1$) while for smaller $\gamma$ we observe the suppression of the minigap due to the weak coupling with S. Moreover, the minigap damping is bounded by the generation of a secondary gap appearing for $\epsilon \approx \Delta_0$, similarly to what has been predicted in Refs. 24 and 25. In the following, unless differently stated, we will set $\Gamma = 10^{-4}\Delta_0$ and $\gamma = 10$, as estimated from realistic values of transparent Al/Cu SN interfaces.\textsuperscript{26} For this transmissivity the external magnetic flux $\Phi$ can efficiently modulate the minigap of the DoS in accordance to Eq. (2). Figures 1(d) and 1(e) show this modulation, where a clear quenching of the minigap is visible for $|\Phi| = \Phi_0/2$. This DoS modulation is the working principle of the present device and allows heat transport when the wire is in the normal state (i.e., for $|\Phi| = \Phi_0/2$) whereas it provides large thermal isolation when it is in the superconducting one. Full control over the heat current flowing through the device is one of the peculiar properties of this nanovalue that, different from the other phase-coherent thermal modulators,\textsuperscript{2,28} allows an almost complete quenching of the heat flow. The thermal current ($J$) flowing from the SN ring to the $N_1(S_1)$ electrode [see Fig. 1(a)] can be written as\textsuperscript{27}

$$J = \frac{2}{\pi R_{N1}^2} \int_0^\infty d\epsilon N_{\text{wire}}(\epsilon, \Phi) N(\epsilon) \mathcal{F}(\epsilon), \quad (3)$$

where $N(\epsilon) = 1$ for $N_1$, $N(\epsilon) = \text{Re} \left[ \left(\epsilon + iT\right)/\sqrt{(\epsilon + iT)^2 - \Delta^2} \right]$ for $S_1$, $\mathcal{F}(\epsilon) = \left[f_0(\epsilon, T_L) - f_0(\epsilon, T_R)\right] = \left[1 + \text{exp}\left[\epsilon/k_BT_L\right]\right]^{-1}$ is the Fermi-Dirac distribution function, and $e$ is the electron charge. When the temperature difference between the SN ring and the $N_1(S_1)$ electrode is small, $\delta T \equiv T_L - T_R \ll \Delta$ (i.e., down to $10^{-4}\Delta$) due to the presence of a S-like DoS in the wire which leads to a reduction of quasiparticles available for thermal transport, and which is only limited by the finite value of $\Gamma$. At fixed $T$, $\kappa$ then gradually increases, as displayed in Figs. 2(c) and 2(d), eventually coinciding with $\kappa^N$ by closing the minigap at $\Phi_0/2$. We emphasize that although a heat valve effect could be achieved as well by replacing the $N_1$ electrode with a superconductor $S_1$ [see Fig. 2(b)], the performance of the resulting structure, apart a stronger quenching of $\kappa$ at low $T$, worsen owing to the presence of the energy gap in $S_1$ which severely limits the heat current flow. For this reason in the following we will focus on the properties of the nanovalue implemented with a $N_1$ electrode. In order to obtain large $\kappa$ modulations a tunnel contact between the N wire and $N_1$ is crucial. The presence of a clean metallic contact indeed leads to a drastic
FIG. 2. Comparison between the nanovalve thermal conductance $\kappa$ vs temperature $T$ calculated for a $N_1$ (a), and a $S_1$ (b) electrode. (c) Color plot of $\kappa$ calculated in (a) vs $\Phi$ and $T$ and (d) cross sections of it at selected temperatures $T$.

degradation of the superconducting-like properties of the N-wire due to inverse proximity effect.8

The heat valve efficiency of this setup can be quantified through the phase-dependent thermal conductance ratio (PTC) defined as: 

$$\text{PTC}(T, \Phi) = \frac{\kappa(T, \Phi)}{\kappa(T, 0)}$$

As can be noticed in Figs. 3(a) and 3(c), where the PTC ratio is calculated vs $T$ and $\Phi$, respectively, the nanovalve can be highly efficient at temperatures below $\sim T_c/2$ with a PTC exceeding 100% for $T < 0.2T_c$, and saturating to $\Delta_0/T$ at $T = 0.1T_c$ for $\Phi = \Phi_0/2$, as shown in Fig. 3(b). Moreover, at low temperature, the thermal valve is more sensitive to the magnetic flux $\Phi$, as demonstrated by the sharp open/close transitions appearing around $\sim \Phi_0/2$ in Fig. 3(d).

All the above results have been obtained from Eq. (2), which is valid in the limit of a short N-wire. In the case of an arbitrary length we have solved numerically the Usadel equation (1) in the N region \cite{28,29} to obtain the DOS in the middle of the wire and compute the thermal conductance $\kappa$ from Eq. (3). The solutions are shown in Fig. 4 where the behavior of $\kappa$ in $T$ and $\Phi$ is displayed for different $E_{Th}$. At large $E_{Th}$ the solutions converge to the analytical one (represented by the dashed lines) that well approximates $\kappa$ for $E_{Th} = \Delta_0$. Moreover, the general trend of $\kappa$ in $T$ and $\Phi$ is reproduced also for longer wires ($E_{Th} < \Delta_0$) with a damping of $\kappa$ still three order of magnitude smaller than $\kappa_0$ at low temperatures (i.e., for $T < 0.05T_c$), therefore ensuring full functionality of the thermal nanovalve even for $E_{Th} = 0.25\Delta_0$.

According to the above conditions the experimental realization of our thermal nanovalve can be easily achieved with conventional metals and standard lithographic techniques.9–12 Superconducting tunnel junctions additionally coupled to the SN ring and the $N_1$ electrode, serving either as heaters or thermometers, allow to change and monitor the quasiparticle temperature on both sides of the structure.27 We neglect here the contribution to thermal transport through these probes as they can provide nearly ideal thermal isolation of the nanovalve electrodes.

Figure 5(a) shows the relevant model accounting for thermal transport in the device. Upon intentionally heating the SN ring at $T_L$, the steady-state electron temperature $T_R$ will depend on the heat exchange mechanisms occurring in $N_1$. Below $\sim 1$ K, the energy relaxation mechanism in $N_1$ stems mainly from electron-acoustic phonon interaction,27 $J_{e-ph}(T_R, T_{ph}) = \Sigma V(T_R^n - T_{ph}^n)$, which allows heat exchange between quasiparticle and lattice phonons residing at $T_{ph}$. Above, $\Sigma$ is the material-dependent electron-phonon coupling constant, $V$ is the volume, and $n$ is the characteristic exponent of the $N_1$ metal. In the model we neglect thermal transport mediated by photons30–32 as well as pure heat condution by phonons.33 For any given $T_{ph}$ and $T_L$, the steady-state $T_R(\Phi)$ is then obtained by solving the thermal balance

FIG. 3. Phase-dependent thermal conductance ratio (PTC) vs $T$ calculated for few values of $\Phi$, (a), and for a few values of $\Gamma$ at $\Phi = \Phi_0/2$, (b). (c) PTC vs $\Phi$ and $T$. (d) Representative cross sections of panel (c) at selected temperatures $T$.

FIG. 4. Comparison between the nanovalve thermal conductance $\kappa$ calculated from the solution of the Usadel equations for different $E_{Th}$ (continuous lines) and in the short junction limit (dashed lines) vs $T$ for $\Phi = 0$ (a) and vs $\Phi$ for $T = 0.1T_c$ (b).
equation \(-J(T_L, T_R, \Phi) + J_{\text{c-ph,R}}(T_R, T_{\text{ph}}) = 0\). For the following calculations we assume an aluminum (Al) ring with $\Delta_0 = 200 \, \text{meV}$, $\Gamma = 10^{-4} \, \Delta_0$, $R_T = 100 \, \text{k}\Omega$, $V = 2 \times 10^{-20} \, \text{m}^3$, $n = 6$, and $\Sigma = 4 \times 10^6 \, \text{WK}^{-1}\text{m}^{-3}$ as appropriate for an AlMn N$_1$ electrode. Furthermore, we assume the SNS junction to be in the short limit which, according to the above discussions, properly describes the framework of a realistic nanovalve.

Phase-dependent control of thermal current through the nanovalve is demonstrated by the strong modulation of $T_R(\Phi)$ displayed in Fig. 5(b) for different values of $T_L$ at $T_{\text{ph}} = 20 \, \text{mK}$. In particular, it can exceed 100 mK at $T_L = 200 \, \text{mK}$. The high response of the heat valve, quantified by the flux-to-temperature transfer function $T$ vs. $\Phi$ calculated for selected $T_L$ as shown in Fig. 5(e). Moreover, to quantify the visibility of the temperature modulation induced by the magnetic flux we define the parameter $\nu = \delta T_R / T_{\text{ph}}$, where $\delta T_R = \max[T_R(\Phi)] - \min[T_R(\Phi)]$. A full characterization of $\nu$ as a function of $T_L$ and $T_{\text{ph}}$ is shown in Fig. 5(d). According to the calculations, a sizeable $T_R$ modulation is still visible (\(\nu > 10\%\) up to 300 mK of bath temperature and, differing from the SQUID-based thermal modulator, the visibility is strongly enhanced at lower $T_{\text{ph}}$ exceeding 1000% at 20 mK. Notably, the proximity nanovalve demonstrates good performance also for the temperature regime where $T_L < T_{\text{ph}}$, as shown by the high efficiency and large transfer functions visible in the regions below the white dashed lines of panels (d) and (e).

In summary, we have proposed a thermal nanovalve based on the SQUIPT technology which is able to efficiently conduct or isolate heat depending on the magnitude of an applied magnetic flux. Under experimentally accessible conditions the device can provide full phase control of the thermal conductance, which is unique at cryogenic temperatures. Standard nanolithographic techniques and conventional metals provide a straightforward route towards the implementation of this thermal nanovalve.

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