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Thermal Conductance by the Inverse Proximity Effect in a Superconductor

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We study heat transport in hybrid lateral normal-metal–superconductor–normal-metal structures. We find the thermal conductance of a short superconducting wire to be strongly enhanced beyond the BCS value due to the inverse proximity effect, resulting from contributions of elastic cotunneling and crossed Andreev reflection of quasiparticles. Our measurements agree with a model based on the quasiclassical theory of inhomogeneous superconductivity in the diffusive limit.

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In a bulk superconductor at the lowest temperatures, thermal conductivity is exponentially suppressed compared to the linear temperature dependence expected from the Wiedemann-Franz law [1]. The residual heat conduction at temperatures $k_B T \ll \Delta$ is only due to quasiparticles (QPs) at energies above the superconducting energy gap $\Delta$, whereas Andreev reflection completely blocks the subgap flow of energy [2]. This explains why at such temperatures superconductors are poor conductors of heat, and their thermal conductivity can often be considered negligible. In hybrid mesoscopic structures with small normal-metal islands and short superconducting wires, the picture changes considerably, and heat flow through a superconductor can become essential [3].

When a superconductor (S) is brought into good contact with a normal metal (N) through a transparent metal-to-metal contact, properties of the N are modified by the widely studied proximity effect [4–7]. Close to the interface, also the S is modified by the inverse proximity effect: the energy gap is diminished and the subgap density of states is nonzero [8,9]. Andreev reflection takes place on the scale of the superconducting coherence length $\xi_0$, so that after a distance $L$ into the superconductor a subgap QP survives with probability $\sim e^{-L/\xi_0}$. Thermal conductance from subgap energies is caused by those QPs which have not Andreev reflected back before reaching the other end of the superconductor. This corresponds to a combined effect of elastic cotunneling and crossed Andreev reflection [10], as both processes carry energy current in the same direction. As a result, the QP-mediated thermal relaxation through an S wire of length not much larger than $\xi_0$ is greatly enhanced. Contrary to dying out exponentially at the lowest temperatures, it can dominate over other mechanisms, e.g., electron-phonon (e-ph) relaxation in the N wire.

In this Letter, we report an experimental study of the thermal conductance $G_{th}$ of diffusive S wires under the influence of the inverse proximity effect. This is in contrast to most thermal transport experiments on Andreev interferometers [11–13], where $G_{th}$ depends mainly on the properties of the proximized normal metal, and the focus has been on long range phase coherent effects. Previously, $G_{th}$ of diffuse normal-metal–superconductor–normal-metal (NSN) structures with short S sections of length $L_S \ll \xi_0$ was theoretically investigated in Ref. [14]. Here, $\xi_0 = \sqrt{h \Delta_0 / \Delta}$ with $\Delta_0$ denoting the diffusion constant of the superconductor, and $\Delta_0$ is the bulk energy gap at zero temperature. In this Letter, we focus on S wires with length $L_S \approx \xi_0$ in the diffusive limit $l \ll \xi_0$, $L_S$, where $l$ is the elastic mean free path. Electrical transport in similar NSN structures has recently attracted a lot of theoretical and experimental interest [10,15]. When it comes to thermal transport properties, apart from early experiments on large area NSN sandwiches at higher temperatures [16], quantitative measurements of $G_{th}$ in a lateral NSN structure are, to our knowledge, missing.

To probe $G_{th}$ experimentally, we have fabricated a series of structures similar to the one in Fig. 1(a), which displays a typical sample together with the measurement scheme. The structures consist of two normal metal copper (Cu) islands of length $L_N \approx 2.5–4$ μm, width $W_N \approx 200–250$ nm, and thickness $d_N \approx 25–30$ nm, connected by a short superconducting aluminum (Al) wire of width $W_S \approx 300–400$ nm and thickness $d_S \approx 40–50$ nm, with the length $L_S$ varying from sample to sample. Ends of the S wire are overlapping the N regions over a distance $L_O \approx 200–300$ nm, as illustrated schematically in the inset in Fig. 1(a). When the N islands are held at different temperatures $T_1$ and $T_2$, heat current $P_S$ flows through the superconductor, and for small temperature differences $\Delta T \equiv T_2 - T_1 \ll T \equiv (T_1 + T_2)/2$, one has $G_{th}(T) = P_S / \Delta T$. Besides the direct NS contact to the short Al wire, each N island is connected via aluminum oxide tunnel barriers to four superconducting Al leads. These normal-metal–insulator–superconductor (NIS) tunnel junctions with an area of (150–200) × 200 nm$^2$ and typical normal state resistance $R_T \approx 20–100$ kΩ allow for the measurement of the electronic temperatures $T_1$ (island 1) and $T_2$ (island 2) and creation of the gradient $\Delta T$, as discussed below in more detail.

To calculate $G_{th}$ within the framework of nonequilibrium superconductivity, pair correlations in the S wire are...
described in terms of a position- and energy-dependent complex function $\theta(x, E)$. From a solution of the Usadel equations [4,17,18], it follows that $G_{th}$ of a diffusive S wire of length $l_S = L_S/\xi_0$ between two N reservoirs is given by

$$G_{th} = \frac{G_N}{2k_B T^2 e^2} \int_0^\infty dE E^2 M(E) \text{sech}^2 \left( \frac{E}{2k_B T} \right).$$  \hspace{1cm} (1)

Here, $G_N = R_N^{-1}$ denotes the normal state electrical conductance of the S wire, and $M(E)$ is an energy-dependent heat transparency defined by $M(E)^{-1} = \int_0^{\infty} dx \cos^{-2}[\text{Im}\theta(x, E)]$. The quantity $M(E)$ can be interpreted as the fraction of QPs which are able to diffuse through the S wire from one N reservoir to the other, relative to that in the normal state. In the BCS limit with $l_S \gg 1$, $M(E) = 1$ at $E > \Delta$, and it vanishes below the gap. In that case, defining $y = \Delta/k_B T$, we recover for $y \gg 2$ from Eq. (1) the result

$$G_{th}^{\text{BCS}} \approx 2G_N T(k_B/e)^2(y^2 + 2y + 2)e^{-y}. \hspace{1cm} (2)$$

On the other hand, in the normal state with $M(E) \equiv 1$, Eq. (1) reduces to the Wiedemann-Franz value $G_{th}^{\text{N}} = L_0 G_N T$ with the Lorenz number $L_0 = (\pi^2/3)k_B^2/e^2$.

Neglecting self-consistency of the order parameter and the overlaps of N and S, we can find an analytical approximation for $G_{th}$ which includes subgap heat transport and describes how $M(E)$ starts to deviate from a step function as $l_S$ decreases [18]. At energies $E < \Delta$ we have

$$M(E) \approx 32[\text{Im}\tanh([\theta_S - \theta_0]/4)]^2 b e^{-b} \coth(b/2), \hspace{1cm} (3)$$

with $b = l_S(2\sqrt{\Delta^2 - E^2}/\Delta_0)^{1/2}$, whereas $M(E) \approx 1$ for $E > \Delta$. Here, $\theta_S = \arctanh(\Delta/E)$ and $\theta_0$ are the values of $\theta$ far in the superconductor and close to the NS interface, respectively. The value of $\theta_0$ is found by considering the boundary condition for $\theta$ at the interface. In the limit of vanishing interface resistance it is determined mainly by the quantity $r = A_S \sigma_N^S/A_S \sigma_N^N$, which includes the cross sections and normal state conductivities of the S and N parts. In the zero temperature limit the normalized thermal conductance $G_{th}/G_N^{\text{th}}$ saturates to the constant value $M(0)$ and grows as $\sim T^2$ at low temperatures. For $A_S/\Delta < 1$ and $l_S \approx 4$, we find $M(0) \approx 32(3\sqrt{2} - 4)/l_S \exp(-\sqrt{2}/l_S)$. The result of Eq. (3) with $A_S/\Delta \ll 1$ is compared to non-self-consistent numerical estimates in Fig. 1(b), and we see it to be valid for $l_S \approx 4$. The $G_{th}$ in Fig. 1(c) is consequently obtained by using this $M(E)$ in Eq. (1) and assuming a BCS temperature dependence for $\Delta$. This is shown below to be in fair agreement with experiments, but especially at higher temperatures and for shorter samples self-consistent numerical calculations become necessary.

The samples were fabricated on an oxidized silicon substrate by electron beam lithography and three-angle shadow evaporation of the metals through a suspended resist mask. Based on resistivity measurements, we estimate $D_S \approx 50$–$75$ cm$^2$/s and $l \approx 10$ nm for aluminum. Together with the energy gap $\Delta_0 \approx 200$ $\mu$eV for Al, we have $\xi_0 \approx 100$–$150$ nm. The structures were measured through filtered signal lines in a $^3$He-$^4$He dilution refrigerator with a base temperature below $50$ mK. Here, we present measurements on four samples with the nonoverlapped S length $L_S$ varying in the range $400$ nm–$4$ $\mu$m. We refer to Table I for sample parameters and dimensions. We estimate the interface resistance of the direct transparent NS contacts to be less than $1$ $\Omega$. The strong electron-electron interaction in copper allows us to assume a well-defined local electronic temperature to exist on each island. Because of the relatively small size of the islands, we are able to probe and control these temperatures in the following way: As shown in Fig. 1(a), on each island $i$ one pair of NIS junctions is biased by a battery-powered floating source at a fixed current $I_{th,i} \leq 0.005\Delta_0/eR_F$, $i = 1, 2$. Since QP tunneling in a NIS junction and therefore the current-voltage characteristic is strongly dependent on the normal metal temperature [19], the voltages $V_{th,i}$ act as

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thermometers once calibrated against the cryostat temperature $T_0$ [20]. To create a temperature difference between the islands, the remaining pair of NIS junctions on island 1 is biased by a dc voltage $eV \lesssim 2\Delta$, making this SINIS structure function as an electronic refrigerator [21,22] due to energy-selective QP tunneling. On the other hand, the low bias current of the thermometer does not significantly affect the thermal balance of the island.

Figure 2 displays the measured electronic temperatures $T_i$ for each sample at three representative bath temperatures $T_0$. For all $T_0$ displayed in Fig. 2, a drop in the temperature $T_1$ of island 1 is evident close to $eV \approx 2\Delta$, where the cooling power of the SINIS refrigerator reaches its maximum. At the highest bath temperatures displayed, the temperature $T_2$ of the remote island first closely follows $T_1$, but at lower $T_0$ a strongly $L_S$-dependent difference develops. At the observed electronic temperatures, thermal conduction through the substrate is weak, and a difference between $T_1$ and $T_2$ as a function of $V$ therefore reflects the thermal conductance $G_{th}$ of the S wire. To characterize this thermal link between the islands, we choose to study the temperature drops $\Delta T_i = T_i(V) - T_i(V = 0)$ at the optimal cooler bias voltage as a function of $T_0$. For consistency we performed several measurements on each sample, permitting the pairs of NIS junctions used for thermometry and refrigeration. The ratio $\Delta T_2/\Delta T_1$ has the advantage of being largely insensitive to the cooling power of the refrigerator junctions; i.e., it is unaffected by their $R_T$ or other characteristics.

To analyze the dependence of the relative temperature drop $\Delta T_2/\Delta T_1$ on $T_0$, we utilize the thermal model of Fig. 1(d). Since the bias voltage $V$ of the SINIS refrigerator is swept at a very low rate compared to the $e$-$\text{ph}$ relaxation time, the system reaches a thermal steady state at each $V$, corresponding to the heat balance equations $P_{\text{cool}} - P_S - P_{\text{e-ph,1}} - P_1 = 0$ and $P_S - P_{\text{e-ph,2}} - P_2 = 0$ for island 1 and 2, respectively. We assume the islands to exchange energy via QP heat conduction along the S wire, described by $G_{th}$ and the heat flow $P_S$. In addition, heat is removed from the cooled island, described by the power $P_{\text{cool}}$ [22]. At the optimal cooler bias voltage, typical values of $P_{\text{cool}}$ for the measured samples lie in the range 10–100 fW. Electrons on each island are thermally coupled to the island phonons at $T_0$ via $e$-$\text{ph}$ coupling, modeled by the power flows $P_{\text{e-ph,i}} = \Sigma V_i(T^e_i - T^p_i)$ [23]. Here, $\Sigma \approx 2 \times 10^8$ W K$^{-5}$ m$^{-3}$ [19] is the $e$-$\text{ph}$ coupling constant of Cu, and $V_i$ is the volume of island $i$. Finally, the constant terms $P_i \approx 1$ fW account for unavoidable parasitic heating from the electrical environment. We assume a low Kapitza resistance between the Cu island and substrate phonons, thereby neglecting any lattice cooling or heating. This allows us to fix the phonon temperature to $T_0$, i.e., the cryostat bath temperature. We neglect also the photonic heat conduction, because of mismatched impedances, as well as $e$-$\text{ph}$ coupling within the superconductor due to the short length of the S wires [24].

Figure 3(a) displays the measured $T_0$ dependence of $\Delta T_2/\Delta T_1$ for the four samples. Predictions of the thermal model with $G_{th}$ calculated by using Eqs. (1) and (3) with

\begin{equation}
\frac{\Delta T_i}{\Delta T_1} = \frac{G_{th,i}}{G_{th,1}},
\end{equation}

FIG. 3 (color online). (a) Temperature dependence of the relative temperature drop $\Delta T_2/\Delta T_1$. The symbols show the measured data, whereas the solid, dashed, and dash-dotted lines correspond to the thermal model with $G_{th}$ based on Eq. (3), the $l_S \gg 1$ limit of Eq. (2), and a numerical solution of the Usadel equation, respectively. The error bars are based on the uncertainty in the temperature calibration of the NIS thermometers. (b),(c) $T$ dependence of the $G_{th}$ employed to produce the solid lines in (a), normalized to $G_{th}^N$ in (b) and to $G_{th}^{\text{BCS}}$ in (c).
TABLE I. Sample parameters; see the text for details.

<table>
<thead>
<tr>
<th>Sample</th>
<th>I</th>
<th>II$^a$</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta_0$ [(\mu\text{eV})]</td>
<td>190</td>
<td>230</td>
<td>185</td>
<td>185</td>
</tr>
<tr>
<td>$L_S$ [(\mu\text{m})]</td>
<td>4.2</td>
<td>1.1</td>
<td>0.875</td>
<td>0.425</td>
</tr>
<tr>
<td>$R_N$ [(\Omega)]</td>
<td>15</td>
<td>20</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>$l_S$</td>
<td>30</td>
<td>8</td>
<td>6.5</td>
<td>4</td>
</tr>
</tbody>
</table>

$^a$Metals deposited in a different evaporator for this structure.

$r \approx 2$ are shown in Fig. 3(a) as the solid lines. The dashed lines show the $l_S \gg 1$ limit described by Eq. (2). The lines in Figs. 3(b) and 3(c) further show $G_{\text{th}}$ relative to its normal state and the BCS limit value, respectively. In all cases, the measured temperatures $T_1$ were used as input for solving the heat balance equation of island 2 to obtain $T_2$, and $l_S$ and $R_N$ were treated as fitting parameters with the values indicated in Table I. Similar results are obtained when the cooling power $P_{\text{cool}}$ is calculated theoretically, and both heat balance equations are solved. In Fig. 3(a), the agreement between the model with the analytically approximated $G_{\text{th}}$ (solid lines) and the measurements is reasonable for all the samples. For sample I with largest $l_S$, $\Delta T_2/\Delta T_1$ follows closely the BCS result, similar to sample II with a relatively large $R_N$. Most remarkably, for samples III and IV with the smaller $l_S$, the low temperature behavior of $\Delta T_2/\Delta T_1$ is strongly affected by the inverse proximity. The high values of $\Delta T_2/\Delta T_1$ at the lowest $T_0$ differ drastically from the prediction based on the BCS heat conductance alone (dashed lines). The dash-dotted blue line for sample III is based on $G_{\text{th}}$ obtained from a self-consistent fully numerical solution of the Usadel equation in a 1D proximity circuit, including the overlap regions and the series N wires [18]. Compared to the analytical prediction, the lesser increase in $\Delta T_2/\Delta T_1$ at low temperatures can be partly attributed to an effective increase of $l_S$ due to the proximity effect in the N parts. Linearizing the heat balance equation of island 2 for small $\Delta T$ gives $\Delta T_2/\Delta T_1 \approx G_{\text{th}}/(G_{\text{th}} + G_{\text{ph,2}})$, with $G_{\text{ph,2}} \approx 5\Sigma V_2 T_0$ denoting the e-ph thermal conductance. Comparing the subgap and above-gap contributions of $G_{\text{th}}$ to each other and to $G_{\text{ph,2}}$, one can estimate the significance of the inverse proximity effect at low temperatures. For the long samples I and II with negligible subgap heat transport, $\Delta T_2/\Delta T_1$ drops below 0.5 approximately at the bath temperature at which $G_{\text{ph,2}}$ becomes larger than $G_{\text{th}}$. On the other hand, for samples III and IV, the subgap conductance alone is larger than $G_{\text{ph,2}}$ at all $T_0$ shown in Fig. 3(a), and $\Delta T_2/\Delta T_1$ remains above 0.5.

In summary, we have investigated the thermal conductance of short superconducting wires in the presence of the inverse proximity effect. We find the conductance to be strongly enhanced relative to that expected for a bulk superconductor, complementing earlier work on the thermal conductance of mesoscopic normal-metal wires in close proximity to superconductors. Our study helps understanding heat transport in mesoscopic structures, allowing one to either utilize or avoid the heat flows through proximized superconductors, e.g., in detector applications of hybrid normal-metal–superconductor structures or in electronic refrigeration.

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