
Magnetic-Field-Induced Stabilization of Non-Equilibrium Superconductivity

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A small magnetic field is found to enhance relaxation processes in a superconductor thus stabilizing superconductivity in non-equilibrium conditions. In a normal-metal (N) – insulator – superconductor (S) tunnel junction, applying a field of the order of 100 μT leads to significantly improved cooling of the N island by quasiparticle (QP) tunneling. These findings are attributed to faster QP relaxation within the S electrodes as a result of enhanced QP drain through regions with locally suppressed energy gap due to magnetic vortices in the S leads at some distance from the junction.

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I. INTRODUCTION

In this work, we report an observation that appears counterintuitive at first: a small magnetic field is found to stabilize superconductivity under quasiparticle (QP) injection. In our experiment, the cooling power of normal-metal (N) – insulator (I) – superconductor (S) tunnel structures is enhanced in perpendicular magnetic fields $B_\perp \approx 100 \mu T = 1 \text{G}$. Measured maximum temperature drop $\delta T$ relative to a starting bath temperature $T_0 = 285 \text{ mK}$ exhibiting this behavior is shown in Fig. 1 (a). The improvement is unexpected, as in general the effect of a magnetic field is to suppress superconductivity. Electronic cooling in NIS junctions in the presence of magnetic fields in both perpendicular and parallel orientations has been studied before, but only in higher fields where the cooling power was already reduced due to diminishing superconducting energy gap $\Delta$. On the other hand, the creation of magnetic vortices has been shown to enhance QP relaxation in superconducting aluminum, as the QPs become trapped and thermalize in the regions of reduced energy gap. Here we demonstrate that the additional relaxation channel due to enhanced QP drain through regions occupied by magnetic vortices enhances the superconducting performance of S leads and improves the electronic cooling in NIS junctions. This can be of relevance in superconducting qubits, resonators, and in hybrid SINIS turnstiles in reducing the effects from nonequilibrium and residual QPs arising due to drive and microwave radiation from the environment. Moreover, improved relaxation caused by vortex creation in the S leads can partially explain the “re-entrant superconductivity” observed in Zn and Al nanowires. In the present case, as sketched in Fig. 1 (a), vortex formation in the S leads can partially explain the “re-entrant superconductivity” observed in Zn and Al nanowires. In the present case, as sketched in Fig. 1 (a), vortex formation in the S leads can partially explain the “re-entrant superconductivity” observed in Zn and Al nanowires. In the present case, as sketched in Fig. 1 (a), vortex formation in the S leads can partially explain the “re-entrant superconductivity” observed in Zn and Al nanowires.

In an NIS junction, $\Delta$ acts as an energy filter for the tunneling QPs. At low temperatures $k_B T \ll \Delta$ and for bias voltages $eV \lesssim \Delta$ across the junction, the electrons in the N electrode cool considerably below the phonon temperature by hot QP extraction. The effect can be made more pronounced in a symmetric double junction SINIS structure with a small N island contacted to S leads via two NIS junctions, allowing to construct practical solid-state refrigerators for cooling thin-film detectors to temperatures close to 100 mK.
formance of actual devices depends crucially on the relaxation of the QPs that are injected into the S electrode, as the superconductor overheating diminishes the cooling power at an NIS junction because of enhanced QP back tunneling. The excess QP density close to the junction can be diminished by fabricating the S electrodes very thick\textsuperscript{16}, or covering them partially by a layer of normal metal that acts as a QP trap\textsuperscript{18-20}. The QP population is typically modeled in terms of a diffusion equation, describing their recombination retarded by phonon retrapping, and other loss mechanisms\textsuperscript{21-25}. Converting the excess density into an effective, position-dependent temperature \( T(x) \), one finds\textsuperscript{26,27} that at phonon temperatures \( k_B T \ll \Delta \) the S leads can be overheated on a length scale ranging from tens of micrometers to a millimeter, as the electron-phonon relaxation and electronic heat conduction are exponentially suppressed compared to their normal state values\textsuperscript{22,28}.

II. EXPERIMENT

Here we present data from one of several measured symmetric SINIS structures similar to that shown in Fig. 1 (b), fabricated at different times and electrically characterized in a dilution refrigerator down to 50 mK bath temperature. The same qualitative behavior was observed in all structures with the same geometry. A copper island of area \( A_N \simeq 2.7 \times 0.7 \, \mu m^2 \) is contacted by four overlap-type Al/Al-oxide/CuNIS junctions. The Al electrodes with zero-temperature energy gap \( \Delta_0 \simeq 210 \, \mu eV \) become superconducting below \( T_C \simeq 1.4 \, K \). Compared to the two small (probe) junctions in the middle, the two outer (cooler) junctions at the ends of the island have larger overlap area and therefore lower normal state tunnel resistance \( R_T \simeq 1.1 \, k \Omega \) each. The structures were fabricated on an oxidized silicon substrate by standard electron beam lithography and two-angle shadow evaporation of Al and Cu through a polymer resist mask. First, an Al layer of thickness \( d_{Al} \simeq 30 \, nm \) was deposited, followed by \textit{in situ} oxidation in the \( e \)-beam evaporator chamber in a few millibars of pure oxygen for a few minutes. Finally, a Cu layer of thickness \( d_C \simeq 30 \, nm \) was evaporated at a different angle, forming the N island with four tunnel contacts to the Al electrodes. In addition, Cu replicas of the Al leads form large area tunnel junctions by partly covering the Al layer, serving as QP traps, albeit of suboptimal performance\textsuperscript{19}.

The island electron temperature \( T_N \) is measured by biasing the probe junctions by a constant current \( I_{th} \), and measuring the voltage drop \( V_{th} \), calibrated against \( T_0 \) at \( V = 0 \). The solid lines in Fig. 2 (a) show the measured \( T_N \) as a function of \( V \) at bath temperatures \( T_0 \) between 0.1 and 0.5 K, in zero field (red) and at \( B\perp = 3 \, G \) (blue). In the following, the minimum \( T_N \) along each curve at a fixed \( T_0 \) is denoted by \( T_{N,\text{min}} \), and the corresponding bias voltage by \( V_{\text{opt}} \). The strong influence of small \( B\perp \) on the cooling is evident: At \( eV \simeq 2\Delta \) the maximum cooling \( \delta T = T_{N,\text{min}} - T_{N,0} \) at each \( T_0 \) increases by several tens of percents. The cooler QP current displays analogous behavior, Fig. 2 (b). At the same time the optimum bias voltage \( V_{\text{opt}} \) increases, Fig. 2 (d), while heating at \( V > V_{\text{opt}} \) diminishes. The cooling enhancement is symmetric in the applied field.

The improved refrigeration is summarized in Fig. 2 (c), where the symbols show the \( T_0 \)-dependent relative minimum temperature in zero field and close to optimum \( B\perp \). We observed the improved cooling also with Ag as the normal metal, in single NIS junctions with various gradually widening lead geometries close to the junction, and in a parallel field. In the latter case, the required fields were larger by an order of magnitude and dependent on the field orientation in the sample plane.

The thin-film Al leads behave as a type II superconductor, so that \( B\perp \) penetrates in the form of vortices\textsuperscript{29,30}. Based on a typical normal state resistivity \( \rho = 3.5 \, \mu \Omega cm \) of our Al at 4.2 K\textsuperscript{31,32}, the elastic mean free path is \( l \simeq 8 \, nm \). With the Bardeen-Cooper-Schrieffer (BCS) coherence length \( \xi_0 \simeq 1600 \, nm \) and the London penetration depth \( \lambda_L \simeq 16 \, nm \) for bulk pure Al at low-
temperatures, one obtains $\xi = 0.855(\xi_d)^{1/2} \approx 100$ nm and $\lambda = \lambda_d(\xi_d/\ell)^{1/2} \approx 230$ nm for our Al films with the Ginzburg-Landau parameter $\kappa = \lambda/\xi \approx 2.4 > 1/\sqrt{2}$ and the lower critical field for the bulk material $H_{c1} \lesssim 100$ G. As sketched in Fig. 1 (a), the S leads of the cooler junctions have an initial width of approximately 1 \mu m. At a distance of 1 \mu m away from the island, they widen to 2.5 \mu m width and continue for 15 \mu m before again widening to 10 \mu m width and connecting to large-area bonding pads further 350 \mu m away. The magnetic field below which vortices are completely expelled from a long and narrow S lead of width $W$ is of the order of $B_0 = \Phi_0/W^2$ and where $\Phi_0 \approx h/(2e) \approx 2 \times 10^{-15}$ Wb is the magnetic flux quantum. For a strip of width $W = 10$ \mu m, we find $B_0 \approx 0.2$ G, whereas $W = 2.5$ \mu m results in $B_0 \approx 3.3$ G. Taking into account the demagnetizing factor $1 - n_z \approx (0.5...2) \times 10^{-2}$ of our films we can conclude that the initial increase in $|\delta T|$ in Fig. 1 (a) observed below 1 G and the turn-back that starts close to 3 G are consistent with vortex penetration into the wide and narrow parts of the lead, respectively.

In Ref. 3 with large area NIS junctions, the increased sub-gap conductance at small $B_L$ could be directly associated with the fraction of vortices in the junction area. In contrast, we do not observe an increase in the cooler junction sub-gap current in the small fields. The thermometer junctions with narrower S electrodes are not considerably affected in fields $B_L \lesssim 10$ G even at bias voltages close to $2\Delta$, indicating that vortices exist only further away from these junctions.

### III. THERMAL MODEL

To model the improved cooling, we assume quasiequilibrium with a local electronic temperature different from the bath temperature. The cooling power depends on the temperatures $T_N$ and $T_S$ of N and S electrodes near the interface. They are found from the equation of heat balance in the N island

$$2\dot{Q}_N(V, T_N, T_S) = \Sigma_N \nabla_N \cdot (T_N^5 - T_S^5) + P_0,$$

(1)

and of the heat conduction in each superconducting lead,

$$\nabla \cdot [\kappa \nabla T(x)] = q(x),$$

(2)

with the boundary conditions $\mp \kappa A T'(0) = \dot{Q}_S$, and $T(x) \to T_0$ at $x \to \pm \infty$ for the right or left lead (A is a wire cross section). The temperature of the lead at the interface is $T_S \equiv T(x = 0)$. The first term in the rhs of Eq. (1) describes the heat transferred to phonons in the normal island. The island volume and electron-phonon coupling constant are $\Sigma_N = \Delta_N N_S$ and $\Sigma_N$, respectively. $P_0 \approx 1$ kW in Eq. (1) is a constant residual power due to imperfect RF-filtering of the measurement. The heat $\dot{Q}_N$ extracted from the island through a single NIS junction and the heat $\dot{Q}_S$ injected into an S lead by tunneling are

$$\dot{Q}_{N,S} = \frac{1}{e^2 R_T} \int n_S(E_S) E_{N,S} [f_{T_N}(E_N) - f_{T_S}(E_S)] dE.$$

(3)

Here, $E_N = E - eV/2$, $E_S = E$, $f_{T_S}(E_S)$ is the Fermi occupation factor, and $n_S(E)$ is the normalized BCS density of states (DOS).

The rhs of Eq. (2) is the power transferred from the unit volume of the superconductor into the (unbiased) normal trap with temperature $T_0$. Similarly to Eq. (3),

$$q(x) = \frac{1}{e^2 \rho_{tr} d_S} \int n_S(E) [f_T(E) - f_{T_0}(E)] dE = \left[ E(T) - E(T_0) \right]/\tau_{tr},$$

where $\tau_{tr}^{-1} = 1/(2e^2 N_0 \rho_{tr} d_S)$ is the time of relaxation to the trap, $\rho_{tr}$ being the trap/superconductor tunnel resistance of unit contact area and $N_0$ denotes the normal state DOS at the Fermi energy per one spin projection, while $E(T)$ is the electronic energy of the superconductor with the gap $\Delta$ at temperature $T(x)^{34}$. In Eq. (2) we assume that the electronic subsystem releases heat to the normal trap rather than directly to the phonon bath. Indeed, the trap relaxation rates are $\tau_{tr}^{-1} \approx 10^6...10^7$ s$^{-1}$ for the contact resistances $\rho_{tr} \sim 3...30$ $\Omega \times \mu$m$^2$ while the electron-phonon relaxation rate in aluminium is $\tau_{ph}^{-1} < 3 \times 10^8$ s$^{-1}$ for the experimental temperatures. Equation (2) is obtained by averaging it over inhomogeneities in $\Delta$, assumed to have low areal density and short scale compared to the inelastic relaxation length, i.e., the scale of $T(x)$ variations. The thermal conductivity $\kappa$ and the heat current into the trap $q$ are spatially averaged quantities $\kappa = \kappa_S (1 - r) + \kappa_N r$ and $q = q_S (1 - r) + q_N r$ for a superconductor having a normal fraction $r$ proportional to $B_L$ which models the presence of vortices. The thermal conductivity $\kappa_S$ and $\kappa_N$, and the heat current, $q_S$, of a superconductor at $k_B T \ll \Delta$ are exponentially suppressed relative to their normal-state values $\kappa_N = \mathcal{L}_0 \pi N_0 T$ and $q_S = [(\pi^2 N_0 k_B^2/3)(T^2 - T_0^2)]/\tau_{tr}$ according to $\kappa_S/\kappa_N = (6/\pi^2)(\Delta/k_B T)^2 e^{-\Delta/k_B T}$ and $q_S = (2\pi\Delta)^{3/2} N_0 k_B^2/\tau_{tr}$. Here, $\mathcal{L}_0 = (\pi^2/3)(k_B/e)^2$, and $\sigma_N$ is the Al normal state electrical conductivity.

Because of exponentially small $\kappa_S$ and $q_S$ at $k_B T \ll \Delta$, the temperature $T_S$ can be very sensitive to the vortex fraction $r$. For reference, the black dotted line in Fig. 2 (c) shows the calculated $T_{N,\text{min}}$ as a function of $T_0$ in the limit of perfect thermalization, $T_S = T_{ph} = T_0$. The red and blue solid lines are the results of Eqs. (1) and (2) for equilibrium phonons in the island, $T_{ph} = T_0$. The red line is obtained with $r = 0$, so that the S electrode overheats at most all the way to the large-area bonding pad. Especially towards the lowest bath temperatures, the observed cooling in zero field is considerably weaker than the prediction of the model for perfect thermalization of S electrodes. To estimate the effect in
the optimum field, we set \( r = 1 \) in the 10 \( \mu \text{m} \) wide electrode section, but keep \( r = 0 \) in the narrower section. The result is shown as the solid blue line in Fig. 2 (c). In our samples, a considerable fraction of the N island is located on top of the S electrodes such that \( T_{\text{ph}} \) can be essentially higher than \( T_0 \). As a worst-case estimate, we assume the N island phonons to be overheated to \( T_{\text{ph}} = T_S \). The result for the above two cases of full and partial S electrode overheating are shown as the red and blue dash-dotted lines, respectively. The predicted influence of the field is now stronger, and the measured cooling in both zero and optimum field is bracketed between the solid and the dash-dotted line. Approximate phonon temperatures \( T_{\text{ph}} \) at \( V_{\text{opt}} \) that reproduce exactly the observed \( T_{N,\text{min}} \) are displayed in Fig. 2 (e). In both zero field (red, upper curve) and in the optimum field (lower curve), \( T_{\text{ph}} \) reflects the temperature \( T_S \) of the QPs close to the junction, ranging from close to 0.87\( T_S \) at \( T_0 = 0.1 \) K to around 0.95\( T_S \) at \( T_0 = 0.5 \) K. We stress that the large field-induced improvement evident in Figs. 1 and 2 is observed because of the considerable S electrode overheating in zero field. It causes also the significant increase in \( V_{\text{opt}} \) as \( B_{\perp} \) is increased from zero: \( V_{\text{opt}} \) is close to the ideal value \( 2(\Delta - 0.66k_B T_N)/e \) only at optimum \( B_{\perp} \).

IV. CONCLUSIONS

To emphasize the role of the S electrode geometry, we performed additional experiments on parallel SINIS coolers. As shown in Fig. 3 (a), in a sample with initially wide leads, vortices form first close to the junctions, and applying \( B_{\perp} \) monotonously weakens the cooling. In contrast, with narrow leads close to the junctions as in Fig. 3 (b), the cooling is optimized at a finite \( B_{\perp} \).

In conclusion, we observed that a small magnetic field enhances relaxation processes in a superconductor thus stabilizing superconductivity in non-equilibrium conditions. Significantly improved electronic cooling in a tunnel junction was achieved in a small perpendicular magnetic field. The enhancement of relaxation can be relevant also for “re-entrant superconductivity” observed in Zn nanowires driven out of equilibrium by supercritical current. A quasiequilibrium model accounts for the field-improved QP relaxation in the S leads. The work can provide means for optimizing the performance of superconducting nanostructures, and sheds additional light on the unsolved problem of nonequilibrium and residual quasiparticles.

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