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Efficiency of quasiparticle evacuation in superconducting devices

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The diffusion of excess quasiparticles in a current-biased superconductor strip in proximity to a metallic trap junction is studied. In particular, we have measured accurately the superconductor temperature at a near-gap injection voltage. By analyzing our data quantitatively, we provide a full description of the spatial distribution of excess quasiparticles in the superconductor. We show that a metallic trap junction contributes significantly to the evacuation of excess quasiparticles.

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In a normal metal-insulator-superconductor (N-I-S) junction, charge transport is mainly governed by quasiparticles.[1] The presence of the superconducting energy gap Δ induces an energy selectivity of quasiparticles tunneling.[2,3] The tunnel current is thus accompanied by a heat transfer from the normal metal to the superconductor that is maximum at a voltage bias just below the superconducting gap. For a double-junction geometry (S-I-N-I-S), electrons in the normal metal can typically cool from 300 mK down to $\sim$100 mK.[3–5] However, in all experiments so far, electronic cooling is less efficient than expected.[4,5] It has been proposed that this inefficiency is mostly linked to injected quasiparticles accumulating near the tunnel junction area. This out-of-equilibrium electronic population, injected at an energy above the gap, relaxes by slow processes such as recombination and pair breaking. The accumulation of quasiparticles is aggravated in submicrometer devices, where relaxation processes are restricted by the physical dimensions of the device, leading to an enhanced density of quasiparticles close to the injection point. These quasiparticles can thereafter tunnel back into the normal metal,[6] generating a parasitic power proportional to the current.[7,8] Inefficient evacuation of quasiparticules is also detrimental to the good operation of other superconductor-based devices such as qubits,[9] single-electron transistors,[10] and low-temperature detectors.[11]

In hybrid superconducting devices fabricated by multiple angle evaporation, a normal-metal strip in tunnel contact with a superconducting electrode acts as a trap for excess near-gap quasiparticles, thereby removing them from the superconductor. This mechanism is usually not fully efficient due to the tunnel barrier between the normal metal and the superconductor.[12] A detailed theory of nonequilibrium phenomena in a superconductor in contact with a normal-metal trap has been developed.[8] However, to the best of our knowledge, a quantitative comparison between experiments and theory is so far still missing.

In this Rapid Communication, we present an experimental investigation of the diffusion of out-of-equilibrium quasiparticles in a superconducting strip covered with a quasiparticle trap. A N-I-S junction is used to inject quasiparticles in the superconducting strip. The local superconductor temperature is inferred from the heating of the central N island of a S-I-N-I-S junction. We quantitatively compare our experimental data with a recently discussed theoretical model.[7]

We have used one S-I-N-I-S device with a geometry similar to the one studied in Ref. 13 (see Fig. 1). It is fabricated using electron beam lithography, two-angle shadow evaporation, and lift-off on a silicon substrate having 500-nm-thick oxide on it. The central normal-metal Cu electrode is 0.3 μm wide, 0.05 μm thick, and 4 μm long. The 27-μm-long symmetric superconducting strips of Al are partially covered, through a tunnel barrier, by a Cu strip acting as a quasiparticle trap. At their extremity, the strips are connected to a contact pad acting as a reservoir. Moreover, we added normal-metal Cu tunnel injector junctions of area $\sim$0.09 μm^2 on one of the two strips. Injectors 1 and 2 are at a distance of $a = 5$ and 21 μm, respectively, from the central Cu island. As the tunnel barrier is assumed to be identical in every junction, they have similar specific tunnel resistance. The normal-state resistance of the double-junction S-I-N-I-S test junction and injector junctions 1 and 2 are, respectively, 1.9, 2.5, and 2.3 kΩ. The diffusion coefficient D of the Al superconducting strip film was measured to be 30×10^{-4} m^2/s at 4.2 K.

The total current flowing through a N-I-S junction is the sum of a voltage-independent current related to charge imbalance in the superconductor and a voltage-dependent quasiparticle current:

$$I(V) = \frac{1}{eR_N}\int_0^{\infty} n_S(E)[f_N(E-eV) - f_N(E+eV)]dE, \tag{1}$$

where R_N is the normal-state resistance, f_N is the electron energy distribution in the normal metal, and n_S is the normalized density of states in the superconductor. In the present work, we have subtracted the small current measured at zero bias, thereby removing the contribution of charge imbalance.

In a superconducting wire undergoing quasiparticle injection, the superconductor gap Δ is suppressed locally. As this gap can be extracted from a N-I-S junction current-voltage characteristic, such a junction can be used for quasiparticle detection. Usually, an effective superconductor temperature T_S is then inferred from the superconductor gap-temperature dependence. Figure 2(a) displays the differential conductance dI/dV of a N-I-S junction [similar to an injector in Fig. 1(a)] located on a superconducting strip at different injection voltages for the S-I-N-I-S junction. At high injection, the gap

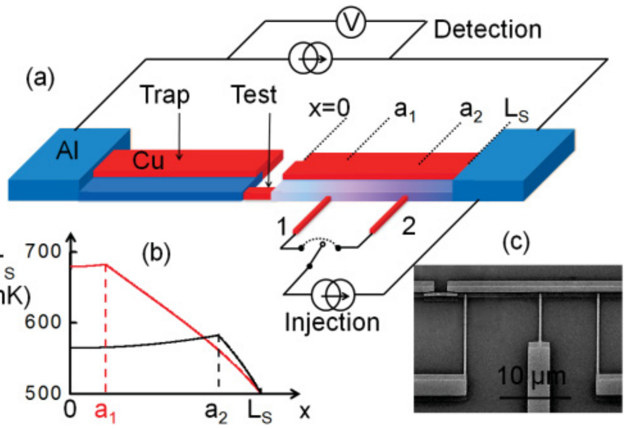

FIG. 1. (Color online) (a) Schematic of the sample design. The test, injector, and trap junctions have a tunnel barrier in between the normal-metal Cu and the superconductor Al electrodes. (b) Spatial profile of the effective superconductor temperature T_S calculated for sample parameters at a bath temperature $T_{bath} = 500$ mK. The two injectors biased at $eV/\Delta = 4$ are in contact with the superconducting strip of length $L_S = 27$ μm, and at a distance $a_1 = 5$ μm or $a_2 = 21$ μm from the test junction. (c) Scanning electron micrograph of a complete device with three injector junctions.

suppression appears clearly, and enables a good determination of the superconductor effective temperature. This approach was used in numerous previous studies.[14–17] At a lower injection voltage, close to the gap, the characteristic becomes less sensitive to quasiparticle injection. For instance, in Fig. 2(a), the probe junction characteristic at a 1-mV injection voltage almost overlaps the equilibrium one (at 0 mV). This limitation comes naturally from the saturation of the superconducting gap at low temperature $T_S \ll T_c$, where T_c is the superconductor critical temperature. This lack of sensitivity has been a major roadblock in investigating the decay of quasiparticles injected at energies just above the gap.[15–17]

A better detection sensitivity can be achieved by measuring the temperature of a small normal-metal island connected to the superconductor through a tunnel barrier.[18] When the superconductor is under injection, some of its excess quasiparticle population will escape by tunneling (even at zero bias) to the normal-metal island. In this Cu island, the phase coherence time of ∼200 ps (measured from a weak localization experiment in a wire from the same material) is assumed to be of the same order as the energy relaxation time. The latter is much shorter than the mean escape time, which was calculated to be ∼100 ns. The injected quasiparticle population will then reach a quasiequilibrium with an electronic temperature T_N that is different from the cryostat temperature T_{bath}.

In this study, N-I-S junctions located on one superconducting strip of a S-I-N-I-S junction are used as quasiparticle injectors by current biasing them. This leads to a spatial distribution of the excess quasiparticle density along the strip. Here, we have chosen to describe this out-of-equilibrium regime through an effective superconductor temperature satisfying the equilibrium relation between quasiparticle density and temperature: $N_{qp0}(T_S) = N(E_F)\Delta(\pi k T_S/2\Delta)^{1/2}\exp[-\Delta/kT_S]$ ($T_S < T_c$), where N_{qp0} is the quasiparticle density and $N(E_F)$ is the density of states at the Fermi level. As discussed above, the central normal metal of the S-I-N-I-S test junction will be used as a detector.

Figure 2(b) shows the differential conductance of the S-I-N-I-S test junction (solid black lines) at different injector-2 bias voltages along with isotherms (dotted red lines) calculated from Eq. (1). Figure 3(a) displays the central normal-metal temperature, extracted from the zero-bias conductance, as a function of injector bias voltage. As this bias increases, the temperature T_N increases above the bath temperature

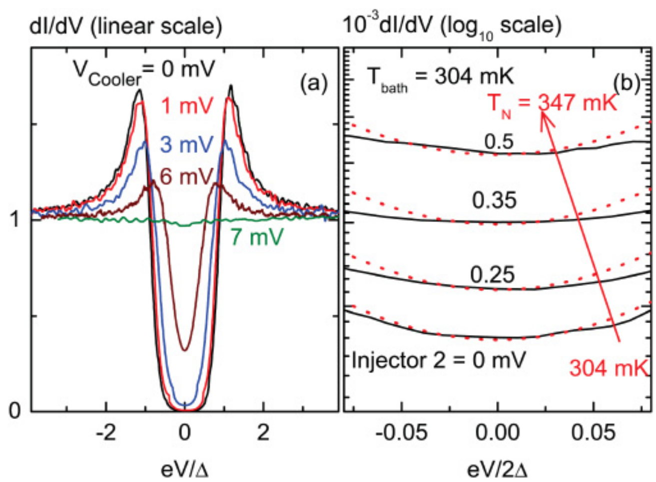

FIG. 2. (Color online) (a) Probe junction differential conductance under different injection bias voltages from the S-I-N-I-S junction. (b) Low-bias differential conductance (on a log scale) of a S-I-N-I-S test junction (solid black lines) at different injector-2 bias voltages, compared to calculated isotherms at different T_N (red dashed lines) obtained from Eq. (1) with $\Delta = 0.22$ meV. Differential conductance dI/dV has been normalized by multiplying by the normal-state resistance R_N.

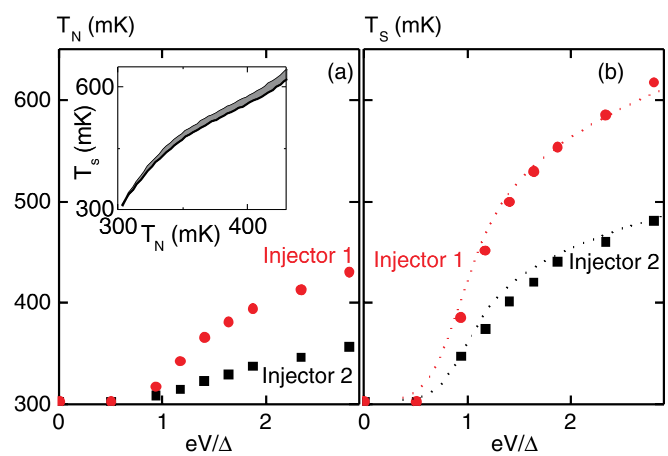

FIG. 3. (Color online) (a) Central N-metal electronic temperature T_N dependence on injector-2 bias voltage at a bath temperature of 304 mK. The error in T_N is smaller than the symbol size. Inset: Calibration of the extracted superconductor temperature T_S to the measured normal-metal temperature T_N. The gray area shows the uncertainty for different values of the Kapitza coupling coefficient. (b) Corresponding extracted superconductor temperature T_S at $x = 0$. The dotted lines are fits using $D_{qp} = 35 \times 10^{-4}$ m^2/s.

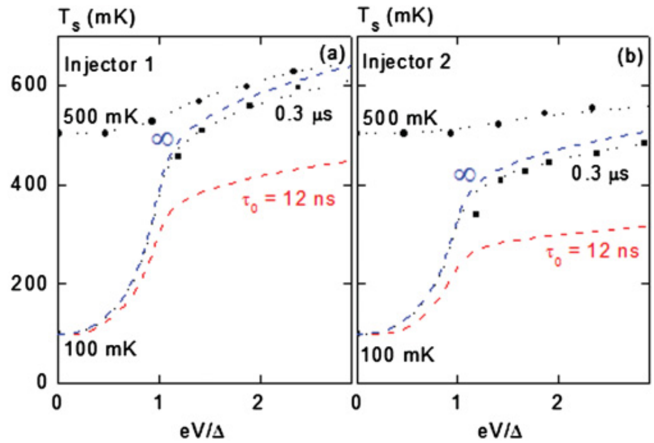

FIG. 4. (Color online) Extracted superconductor temperature T_S as a function of injector bias voltage at a cryostat temperature of 100 mK (squares) and 500 mK (circles). (a) and (b) correspond to an injection from injectors 1 and 2, respectively. The dotted lines show the fits with the parameter $D_{\text{qp}} = 35 \times 10^{-4}$ m^2/s. The red/gray and blue/dark gray dashed lines are the calculated curves with the same D_{qp} value and for $\tau_0 = 12$ ns and ∞, respectively.

T_{bath}, indicating that more quasiparticles tunnel from the superconducting strip to the normal-metal island.

In order to obtain the superconductor temperature T_{S} at the test junction edge ($x = 0$), we need to consider the heat balance in the normal metal. The heat flow across a N-I-S junction with different quasiparticle distribution on either side of the tunnel barrier is given by

$$P_{\text{heat}}(T_{\text{N}}, T_{\text{S}}) = \frac{1}{e^2 R_{\text{N}}} \int_{-\infty}^{\infty} E n_{\text{S}}(E)[f_{\text{N}}(E) - f_{\text{S}}(E)] dE, \tag{2}$$

where f_{S} is the energy distribution function in the superconductor at temperature T_{S}. It is compensated by electron-phonon coupling power $P_{e\text{-ph}}$. We have used its usual expression $P_{e\text{-ph}} = \Sigma U(T_{\text{N}}^5 - T_{\text{ph}}^5)$, where $\Sigma = 2$ nW μm^{-3} K^{-5} in Cu is a material-dependent constant and U is the metal volume. For the normal-metal phonons, the electron-phonon coupling power is compensated by the Kapitza resistance $P_K = KA(T_{\text{bath}}^4 - T_{\text{ph}}^4)$, where K is an interface-dependent parameter and A is the contact area. The inset of Fig. 3(a) displays the calculated correspondence between the superconductor temperature T_{S} and the central N-metal temperature T_{N}. The solid line uses the fitted Kapitza coupling parameter value $KA = 144$ pW K^{-4} found in Ref. 13 in a very similar sample, while the gray area shows the calibration variation for values ranging from 120 W m^{-2} K^{-4} to infinity. The uncertainty in T_{S} due to uncertainty in K is negligible below 400 mK and only 15 mK at 600 mK.

Figures 3(b) and 4 show the extracted superconductor temperature T_{S} at the test junction edge ($x = 0$) for different injection biases, in the two injectors at three different bath temperatures $T_{\text{bath}} = 100$, 304, and 500 mK. For a given injection bias, the temperature T_{S} at the test junction at $x = 0$ is higher for a closer injector. This confirms qualitatively the diffusion-based relaxation of hot quasiparticles in the superconductor. Here, we have succeeded in obtaining accurately the superconductor temperature for an injection bias voltage close to the gap voltage. This sensitivity persists down to a bath temperature of ~200 mK, where the S-I-N-I-S junction current becomes dominated by the Andreev current.[13]

Let us now discuss the spatial evolution of the quasiparticle density N_{qp}. In an out-of-equilibrium superconductor, it is coupled to the phonon density of 2Δ energy $N_{2\Delta}$ through the well-known Rothwarf-Taylor (R-T) equations.[19] In a recent work,[7] some of us have extended the R-T model to include the influence of a trap junction on quasiparticle diffusion. We considered a superconducting strip covered by a second normal metal separated by a tunnel barrier, which is, in practice, equivalent to our device geometry.[3] The normalized excess spatial quasiparticle density $z(x) = N_{\text{qp}}/N_{\text{qp0}} - 1$ in the superconducting strip is then given by the solution of the differential equation

$$D_{\text{qp}} \frac{d^2 z}{dx^2} = \frac{z}{\tau_0} + \frac{z + z^2/2}{\tau_{\text{eff}}}, \tag{3}$$

where D_{qp} is the quasiparticle diffusion constant. From this equation, one can find the quasiparticle decay length $\lambda = \sqrt{D_{\text{qp}}\tau_{\text{eff}}/\alpha}$, where τ_{eff} is the material-dependent effective recombination time and $\alpha = 1 + \tau_{\text{eff}}/\tau_0$ is the enhancement ratio of the quasiparticle decay rate due to the presence of the trap. When trapping is dominant, the quasiparticle decay length reduces to $\sqrt{D_{\text{qp}}\tau_0}$. The trap characteristic time τ_0 describes the rate of quasiparticles escaping to the N-metal trap. It is defined as $\tau_0 = e^2 R_{NN} N(E_F) d_{\text{S}}$, where R_{NN} is the specific resistance of the trap junction and d_{S} is the thickness of the superconductor.

In our experiment, the injectors are biased just above the gap voltage. We assumed that the injected quasiparticles relax fast (in comparison to other recombination processes) to the superconductor gap energy level and thus can be afterward adequately described by the coupled R-T equations. To compare our experimental result with the theoretical model, we have solved Eq. (3) numerically with boundary conditions so as to include the following: the injection, $\frac{dz}{dx}|_+ - \frac{dz}{dx}|_- = \frac{I_{\text{inj}}}{\lambda}$ at $x = a$; the detection, $\frac{dz}{dx} = 0$ at $x = 0$; and the finite length of the strip, $z = 0$ at $x = L_{\text{S}}$. The latter boundary condition accounts for relaxation in the reservoir as an additional path for excess quasiparticle evacuation in addition to trapping. Finally, and as already discussed, the local quasiparticle density $N_{\text{qp}}(x)$ is described as an equilibrium quasiparticle density N_{qp0} so that $N_{\text{qp}}(x = 0) = N_{\text{qp0}}(T = T_S)$ in order to obtain the effective temperature T_{S}.[20] As an example, Fig. 1(b) displays the calculated effective superconductor temperature profile for the sample parameters and at a bath temperature of 500 mK.

In the calculation, we used the calculated values of τ_{eff} and τ_0. The calculated effective recombination time for Al $\tau_{\text{eff}} = 14$ μs (Ref. 21) is close to experimental values.[16,22,23] For our sample parameters, the calculated trap characteristic time τ_0 is equal to 0.3 μs. The model has then only one free parameter, that is, the quasiparticle diffusion coefficient D_{qp}. We obtain a quantitative agreement between the experimental data and the theoretical predictions for $D_{\text{qp}} = 35 \times 10^{-4}$ m^2/s [dotted lines in Figs. 3(b) and 4] on the two injectors and for a bath temperature of 100–500 mK. The fit-derived value of D_{qp} is comparable to the measured diffusion coefficient for Al, and corresponds to $\lambda = 30\ \mu$m.

This leads us to the following understanding. Quasiparticles relax mostly through two channels: trapping in the normal-metal trap (decay length λ) and absorption in the reservoir (decay length L_S). In our device, the decay length of both channels is $\sim 30\ \mu$m, and thus they act with a similar efficiency. In order to gain more insight on this point, Fig. 4 also shows the calculated superconductor temperature T_S at $T_{bath} = 100$ mK for the our sample parameters but with a more transparent trap junction with $\tau_0 = 12$ ns and in the absence of trap $\tau_0 = \infty$. For $\tau_0 = \infty$, the excess quasiparticles relax at the reservoir $x = L_S$. For $\tau_0 = 12$ ns, the decay length is $\lambda = 6.5\ \mu$m, which means that trapping then dominates the quasiparticle absorption. However, at such transparency, the influence of the proximity effect cannot be ignored.[8]

In conclusion, we have studied experimentally the diffusion of quasiparticles injected in a superconductor with an energy close to the gap voltage Δ in the presence of normal-metal trap traps. Our study demonstrates that, in such devices, quasiparticle trapping competes with relaxation in the reservoir. This knowledge is of importance in improving the geometry of future cooling devices and other superconductor-based low-temperature devices.

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