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Resistive transition of niobium superconducting hot-electron bolometer mixers

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We present a model for the description of the resistive transition in hot-electron bolometer mixers. We show that the transition is a property of a superconducting microbridge connected to normal conducting cooling pads. Using the concepts of the superconducting proximity effect, charge-imbalance generation, and Andreev reflection, we have calculated the resistance versus temperature of the device and demonstrate its dependence on the length of the microbridge, both theoretically and experimentally. The analysis reopens the question of the relationship between the resistive transition and the situation in which the device is optimally operated as a heterodyne mixer.
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The increasing demand for sensitive heterodyne receivers in the THz frequency range has stimulated the development of hot-electron bolometer (HEB) mixers. HEB mixers are now generally considered as the most promising candidates for heterodyne applications in this frequency range and have already shown excellent noise performance up to 2.5 THz.[1–4] Also, the intermediate frequency (IF) bandwidth of HEB mixers can reach several GHz,[5] which is large enough for many practical applications.

Two types of HEB mixers are currently being explored: the first type uses electron-phonon coupling as a relaxation mechanism for the hot electrons,[6] whereas the second type uses outdiffusion of the hot electrons to normal conducting cooling pads.[7] Although the cooling mechanism for the two types is different, the response of the mixer in operation is, in both cases, the result of a resistive state in which the resistance of the bolometer is strongly dependent on the temperature of the electrons. Experimentally, the dependence is commonly determined by measuring the dc resistance versus temperature, $R(T)$, of the device.

Limiting factors with respect to the sensitivity of both types of devices are discussed in several theoretical models.[7,8] In these models, the $R(T)$ curve is represented by a brokenline transition, i.e., $dR/dT = R_N/\Delta T_c$, where R_N is the normal state resistance of the device and ΔT_c is the width of the superconducting transition. Using this simplification of the $R(T)$ curve, it is possible to derive expressions for the noise contributions from Johnson noise and thermal fluctuation noise, essentially in terms of the critical temperature T_c, the width of the transition ΔT_c, and the operating temperature T_B. It is therefore clear that, within the present understanding of the operation of HEB mixers, the resistive transition plays a central role with regard to the sensitivity of the device. In this letter we present a model that describes microscopically the superconducting transition of a Nb HEB. We show how the resistance is a function of both temperature and the length of the microbridge.

The typical layout of a Nb HEB mixer is shown in Fig. 1(a). The device consists of a superconducting Nb microbridge attached to normal conducting Au electrodes. Due to the fabrication procedure, the Nb usually extends under the electrodes. The thickness of the Nb is typically 10 nm and the Au contacts are usually 50–100 nm thick. When measuring the resistive transition of the structure, one expects to observe two transitions: one of the bridge and one of the

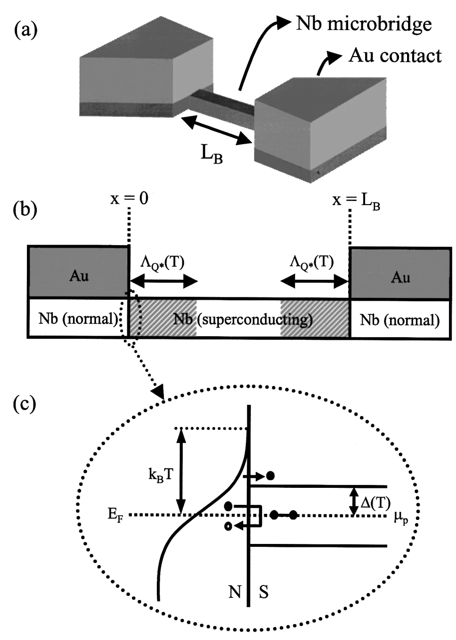

FIG. 1. (a) Common layout of the core of a Nb HEB mixer. Shown are the Nb microbridge and the Au contacts. (b) Cross section of the device at temperatures where the Nb under the Au pads is normal conducting and the bridge is superconducting. (c) Electronic transport processes at a NS interface: electrons with energies $E > \Delta_s$ are injected as quasiparticles and contribute to a dissipative current inside the superconductor, whereas Andreev reflection occurs for energies $E < \Delta_s$.

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parts of Nb covered with Au which have a lower critical temperature due to the superconducting proximity effect. The reduction of T_c depends on the electronic properties of both materials, the thickness of both layers, and the transparency of their interface. A reduced transparency will result in a weaker suppression of the critical temperature of the thin Nb film.[9,10]

At temperatures between the two transitions, the device is essentially a normal metal-superconductor-normal metal (NSN) junction. The NS interface at each side of the junction is formed between Nb in the normal state and the superconducting state [Fig. 1(b)]. In what follows, we will first focus on electronic processes at the interface and then use these insights to calculate the resistance of a NSN junction near T_c.

If a current is passed through a NS interface, the normal current is gradually converted into a supercurrent by means of Andreev reflection; an incident electron with an energy smaller than the superconducting gap Δ_s is converted into a Cooper pair and a hole is reflected, retracing the path of the electron. At temperatures close to T_c, however, Δ_s becomes smaller than $k_B T$ and a substantial fraction of the current is injected as a quasiparticle current [Fig. 1(c)], leading to an imbalance of the quasiparticle charge density inside the superconductor.[11] To compensate for the excess charge, the electrochemical potential of the quasiparticles (μ_{qp}) and Cooper pairs (μ_p) shift in opposite directions, leading to a *measurable* potential difference given by[12]

$$\Delta\mu(x)=\mu_{\mathrm{qp}}(x)-\mu_p=\frac{Q^*}{2N_0}. \tag{1}$$

Here Q^* is the excess charge and N_0 is the density of states per spin at the Fermi energy. Charge-imbalance relaxation can occur via inelastic scattering processes and its characteristic time is given by

$$\tau_{Q*}=\frac{4k_BT}{\pi\Delta_s(T)}\,\tau_{\mathrm{in}}, \tag{2}$$

where τ_{in} is the inelastic scattering time at the Fermi energy. The associated diffusion length is given by $\Lambda_{Q*}(T)=\sqrt{D\tau_{Q*}(T)}$, with D the electronic diffusion constant. In essence, $\Lambda_{Q*}(T)$ represents the length over which the current inside the superconductor is dissipative.

Let us now consider a NSN junction, where the S part is a microbridge with length L_B. Charge-imbalance generation inside the microbridge is governed by the diffusion equation[13]

$$D\,\frac{d^2\Delta\mu(x)}{dx^2}=\frac{\Delta\mu(x)}{\tau_{Q*}}. \tag{3}$$

Since the current at the NS interface is conserved, we use $d[\Delta\mu(x)]/dx=j_{\mathrm{qp}}e/\sigma_n$ as boundary conditions for Eq. (3) at $x=0, L_B$. Here j_{qp} is the quasiparticle current density, e is the electronic charge, and σ_n is the normal state conductivity of the microbridge. We have assumed that all current is injected as a quasiparticle current (i.e., $\Delta_s \ll k_BT$) and that τ_{Q*} is independent of position. Solving Eq. (3) with these boundary conditions yields an expression for the potential drop along the microbridge due to charge imbalance, and thus, for the resistance. We find that

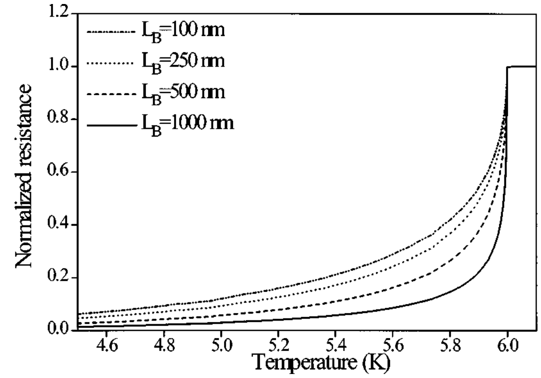

FIG. 2. Normalized resistance as a function of temperature for a Nb HEB. The calculation is performed for different lengths of the microbridge.

$$R_B^*(T)=\Lambda_{Q*}(T)\left(\frac{2R_\square}{w}\right)\frac{\cosh\left(\frac{L_B}{\Lambda_{Q*}(T)}\right)-1}{\sinh\left(\frac{L_B}{\Lambda_{Q*}(T)}\right)}, \tag{4}$$

where $R_\square$ and w are the square resistance and the width of the microbridge, respectively. However, when the temperature is decreased, the superconducting gap opens and an increasing part of the current at the interface is converted to a Cooper-pair current by means of Andreev reflection. We take the opening of the gap into account by using $j_{\mathrm{qp}}=F^*(T)j_b$, where j_b is the bias current. For $F^*(T)$ we use a result from Blonder *et al.*,[14] who calculate the charge-imbalance generation inside the superconductor as a fraction of the total current for arbitrary strength of the barrier at the interface. In our case it is assumed that there is no barrier, because the interface is formed between Nb in the normal and superconducting state [Fig. 1(b)]. It can easily be shown that the resistance of the microbridge is now given by $R_B(T)=F^*(T)R_B^*(T)$.

Figure 2 shows the calculated resistance as a function of temperature for microbridges of different lengths. We use a value of 6 K for the critical temperature of the Nb microbridge. The diffusion constant is independently determined to be 1.6 cm^2/s by measuring the temperature dependence of the critical magnetic field, H_{c2}, of a large 10 nm thick Nb film. In the calculation we assume that the inelastic scattering rate is dominated by electron–electron interactions.[7] We approximate the scattering time by $\tau_{\mathrm{in}}^{-1}=10^8\,R_\square T$.[15] From the calculation one recognizes that the contribution of charge imbalance to the resistance increases with increasing temperature and decreasing length.

To test the predictions of our model, we measure the $R(T)$ curves of Nb microbridges (thickness 10 nm) with varying length contacted by Au pads (thickness 75 nm). The devices are fabricated using a two-step electron beam lithography (EBL) process.[16] The dc resistive transition of the devices is measured using a standard lock-in technique and low bias-current conditions ($\leq 1\ \mu$A) in order to avoid self-heating.

The result for a 160 nm long bridge is shown in Fig. 3(a). Reasonable agreement between experiment and model is found, except for temperatures above 5.7 K and below 4.7 K. The deviation below 4.7 K is well understood: the Nb under the Au pads is becoming superconducting and the total

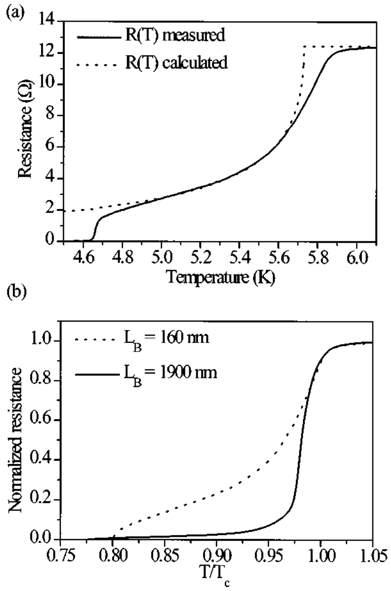

FIG. 3. (a) Comparison of the model with experimental data. The figure shows the measured and calculated $R(T)$ curve for a 160 nm long microbridge. (b) Experimental $R(T)$ of a long (1900 nm) and short (160 nm) microbridge. The data are normalized to T_c and to the normal state resistance of each bridge.

resistance drops to zero. Several factors can contribute to the observed differences beyond 5.7 K. In the model it is assumed that there is no spatial variation of Δ_s along the microbridge. This is correct, except for temperatures very close to T_c, where the coherence length diverges. In that case, it is possible that charge imbalance does not only relax via inelastic scattering, but also via elastic scattering processes.[17] Also, close to T_c, we often observe a ''rounding'' of the $R(T)$ curve. The physical reason for this is not clear, but superconducting fluctuations might contribute. The rounding makes the estimation of T_c in our calculation somewhat arbitrary, since in the model it is assumed that the (intrinsic) superconducting transition of Nb can be described by a step function. Figure 3(b) shows the measured $R(T)$ of a short (160 nm) and a long (1900 nm) bridge. The data are normalized to the normal state resistance of both bridges and to T_c. Here, T_c is defined as the temperature at which the resistance has dropped to 90% of its normal state value. From the figure it is clear that the resistance depends on the length in the same way as predicted by the model (compare Fig. 2).

An important conclusion to be drawn from the analysis is that the resistive transition of a Nb HEB is not a property of the Nb microbridge only, but is strongly influenced by the presence of the normal conducting banks. Our model allows the parameter dR/dT to be calculated, predicting that its value increases with increasing temperature and increasing geometrical length of the microbridge. Since the value of dR/dT represents the linear response of the device, the analysis applies to the case in which the bolometer is operated at a bath temperature close to T_c and using low current conditions.

The lowest noise in heterodyne experiments with HEB mixers is usually measured at bath temperatures well below the (lowest) transition of the detector. The high current density inside the microbridge due to the dc bias current together with the local oscillator signal will lead to high dissipation inside the bridge. However, the Nb–Au banks remain superconducting because the current density there is much lower. Thus, in this situation, the device is in essence a superconductor-normal metal superconductor (SNS) system, instead of a NSN system. As a consequence, charge imbalance no longer determines the resistance and, thus, the dc resistive transition is no longer related to the response of the device. This reopens the question with regard to the nature of the resistive state of the device in heterodyne operation. The answer to this question might be our recent proposal to describe heterodyne mixing in HEBs in terms of an electronic normal hotspot in the superconducting bridge which oscillates at the intermediate frequency.[18]

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