# The resistive transition of aluminium hot electron bolometer mixers with normal metal cooling banks

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**Abstract:**

We perform a theoretical analysis based on the superconducting proximity-effect model for the resistive transition of an aluminium superconducting hot electron bolometer mixer when the cooling banks are in the normal state. We compare our calculated result with a recently reported measurement[1]. Our calculation qualitatively reproduces the observed feature in which the resistance drops quickly around $T_c$ with decreasing temperature, but saturates at a value roughly being one half of the normal state resistance. It also opens the question about which type of cooling banks (normal or superconductor) is favourably for low noise performance.

## I. Introduction

Superconducting hot-electron bolometer (HEB) mixers are currently the best candidates for heterodyne spectrometers operating at frequencies of a few THz. They combine a high sensitivity with the need for only very low local oscillator (LO) power. The operating principle is absorption of radiation by the electrons leading to an elevated electron temperature, which is thermalized to the bath temperature either by phonons (*phonon-cooled*) or diffusion to large cooling pads (*diffusion-cooled*). The elevated temperature, which is a measure of the absorbed power, leads to a resistance change exploiting the difference in resistance between the superconducting state and the normal state. Originally, it was assumed that the devices would be operating at the transition temperature of the superconductor[2]. Later it was recognized that in practice the devices are brought by a bias current into a state in which part of the bridge is normal (*electronic hot spot*) and part is superconducting[3-6]. The mixing results from a modulation of the length of the hot spot with absorbed power.

The mixers used and studied most thoroughly are based on niobium microbridges using large Au cooling pads at both ends (here we focus on diffusion-cooled HEB's). In response to theoretical estimates, predicting a higher sensitivity, broader IF bandwidth, and lower LO power, aluminium has been proposed as an attractive alternative for diffusion-cooled HEB's[1,7-9]. Unfortunately, the mixing results have so far been disappointing suggesting that a good understanding of the behavior of these nano-scaled microbridges consisting of superconducting and normal parts is lacking. In this paper we present a theoretical analysis of the resistive transition of such a system using the microscopic theory of the proximity-effect.

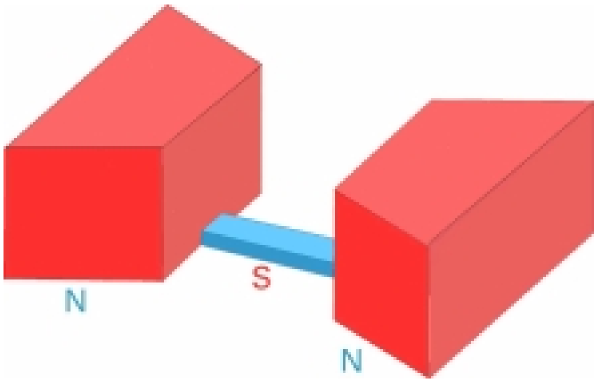


Fig.1. A schematic view of an Al superconducting hot electron bolometer mixer with normal metal cooling banks.

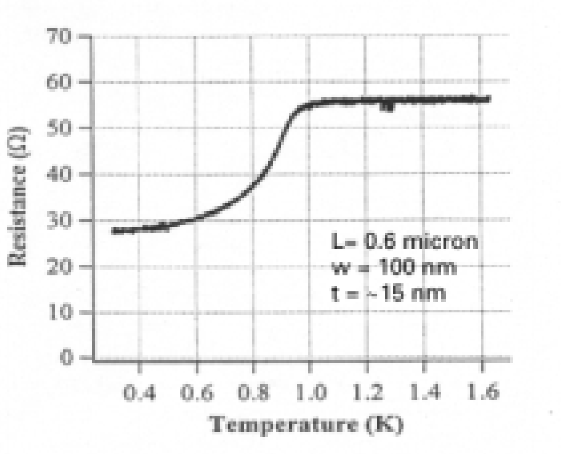


Fig.2. Resistance of 0.6 μm long Al wire as a function of temperature measured by Siddiqi *et al*.[1]

As a starting point we will use a recent observation of Siddiqi *et al*.[1] about the resistive transition of an Al HEB mixer (Fig.2). The resistance drops quickly around a temperature of 1 K, but surprisingly saturates at about 50 % of the normal state resistance even down to very low temperatures. The measured device (Fig.1) consists of a thin, narrow Al microbridge with a length of 600 nm, a width of 100 nm, and a thickness of ~15 nm. The cooling banks are in essence thick and wide Al. The intrinsic superconducting transition temperature of the Al bridge is not exactly known, but expected to be in the range of 1.5-2.4 K. The $T_c$ of the banks is considerably lower than the $T_c$ of the bridge, likely to be ~0.8 K. The diffusion constant of the Al microbridge equals 6 $cm^2/s$. For the curve shown in Fig.2 the superconductivity of the banks is suppressed by applying a magnetic field, which means that the device consists of normal pads with a superconducting microbridge (NSN).

## II. Results of a model-calculation

Since the resistance of the cooling pads is negligible compared to the measured resistance the observations imply that a substantial fraction of the superconducting bridge is resistive. It is well known that the conversion of a normal current to a supercurrent at an N/S interface leads to a resistive contribution due to charge imbalance. This fact has been used by Wilms Floet *et al.*[10] in a previous attempt to model the resistive transition of HEB's. This resistive contribution only appears due to quasiparticles with energies larger than the energy gap and hence, quickly disappears below the critical temperature. Quasiparticles with energies smaller than the energy gap are assumed not to contribute to the resistance and are converted into supercurrent through the process of Andreev-reflection. As pointed out by Siddiqi *et al*[1], their observed anomalous behaviour must be related to the proximity-effect, i.e they find that the measured residual resistance corresponds to a length relating to the coherence length $\xi$(T). A similar observation has previously been made for Pb-Cu-Pb sandwiches by Harding, Pippard, and Tomlinson[11] and subsequently explained by Krähenbühl and Watts-Tobin[12]. This implies that the assumption of Wilms Floet *et al.*[10] of a negligible contribution to the resistance for quasiparticles with energies smaller than the energy gap must be corrected. To proceed the microscopic theory for the proximity effect, based on the Usadel equations supplemented with the appropriate kinetic equation[13] must be used to calculate the spatial variation of the superconducting gap along the microbridge and the resulting contribution to the resistance. Since we intend to focus on the issues of interest to the HEB community we neglect the details of the calculation[14] and present only the results.

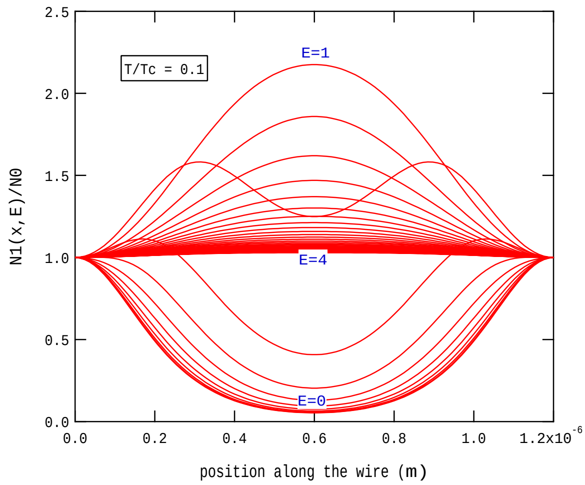


Fig.3. Density of states as a function of position along the bridge for different energies E at $T/T_c = 0.1$.

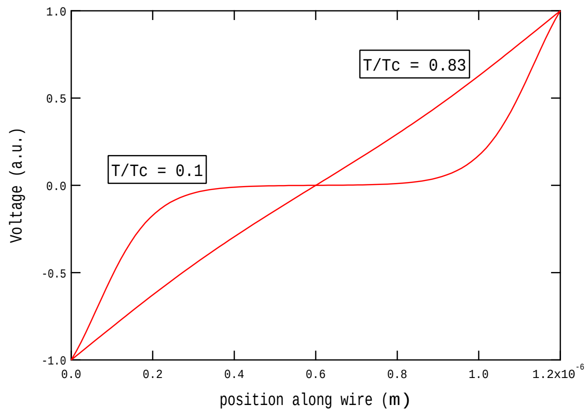


Fig.4. Penetration of the electric field in the bridge at $T/T_c = 0.1$ and 0.83.

Fig.3 shows the calculated density of state at different positions along the microbridge for different energies E, which is normalized to Δ(0), for $T/T_c = 0.1$. (The microbridge is assumed to have a length of 1.2 μm, with a bulk energy-gap of Δ(0) = 0.2 meV, and a diffusion constant 100 $cm^2/s$. $T_c$ is the intrinsic critical temperature of an infinite long bridge consistent with the bulk energy gap). At the boundaries the normal metal density of state is imposed, meaning that Δ is forced to zero in N. Note that even in the middle of the bridge the density of states does not become zero as one would expect for a bulk BCS superconductor. Fig. 4 shows the electrical potential inside the superconducting bridge at $T/T_c = 0.1$ and 0.83. At low temperatures a substantial drop in voltage is found near the interfaces over a length scale somewhat larger than the coherence length at zero temperature $\xi(0)$, given by $0.88(\hbar D/\Delta(0))^{1/2}$. The final and most relevant result of this analysis is shown in Fig. 5.

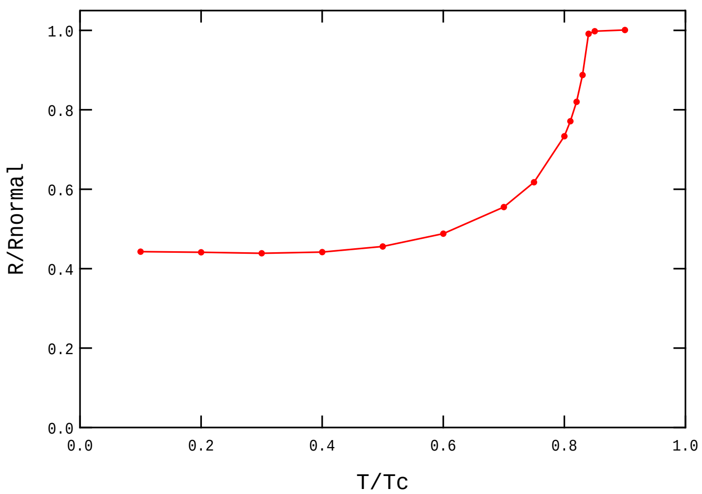


Fig.5. Calculated resistance of an Al bridge (1.2 μm long) when the bath temperature is decreased below $T_c$.

It shows the resistance of the microbridge as a function of temperature, reproducing very well the measured data given in Fig. 2. Note the apparent lower $T_c$ as well as the large residual resistance of about half the normal state resistance. Unfortunately, a one-to-one correspondence to the experimental data cannot be made because the intrinsic $T_c$ of the measured device is not known. Nevertheless, the calculation is believed to contain the essential physics demonstrating the role of the dominant parameter $\xi(0)/L$.

## III. Discussion

The *R-T* curve is an important device characteristic because it provides valuable information about the superconductivity of the bridge and the cooling pads and on the interface between the bridge and the banks. However, this curve is not directly related to the mixer performance. The latter should be determined from the *I-V* curves. Unfortunately, the calculations are performed only for the linear response-regime (zero bias voltage). Nevertheless, the I-V curve is very likely governed by a thermal dissipation process starting at the NS interfaces, which is incompatible with an electronic hot spot concept used successfully for niobium HEB's. Evidently, the proximity effect influences the resistive state stronger for a HEB with a bridge length comparable to $\xi(0)$. Nb devices suffer less from the proximity effect since the length $\xi(0)$ is relatively short.

Over the question about which type of cooling banks (normal or superconductor), although no systematic study has been reported to compare the mixer performance for devices with the cooling banks in the superconducting state or in the normal state, it might be preferable for best sensitivity of also Nb HEB's to work at temperatures where the contacts are superconducting. This analysis suggests that one needs superconducting contacts for good performance of HEB mixers. With superconducting contacts, the electronic hotspot can be formed at the center of the bridge and a high conversion gain is expected from the hot spot mixing model. To avoid heat trapping due to Andreev-reflection, which will reduce the IF bandwidth, the $T_c$ of the banks however should be lower or much lower than that of the bridge.

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