Hotspot mixing: A framework for heterodyne mixing in superconducting hot-electron bolometers

D. Wilms Floet, E. Miedema, T. M. Klapwijk, and J. R. Gao

Citation: Appl. Phys. Lett. **74**, 433 (1999); doi: 10.1063/1.123052
View online: https://doi.org/10.1063/1.123052
View Table of Contents: http://aip.scitation.org/toc/apl/74/3
Published by the American Institute of Physics

APPLIED PHYSICS LETTERS VOLUME 74, NUMBER 3 18 JANUARY 1999

Hotspot mixing: A framework for heterodyne mixing in superconducting hot-electron bolometers

D. Wilms Floet,[a)] E. Miedema, and T. M. Klapwijk
Department of Applied Physics and Materials Science Center, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands

J. R. Gao
Space Research Organization of the Netherlands and Department of Applied Physics, University of Groningen, 9747 AG Groningen, The Netherlands

(Received 18 September 1998; accepted for publication 12 November 1998)

We propose a framework to interpret heterodyne mixing in superconducting hot-electron bolometers. The physical conversion process of the mixer is the result of an electronic hotspot, of which the length, and consequently the resistance, oscillates at the intermediate frequency. On the basis of this concept, we calculate the (un)pumped current–voltage relation, the dc voltage responsivity, and the mixer conversion efficiency. © *1999 American Institute of Physics.* [S0003-6951(99)03603-7]

Despite the significant technological progress in the development of hot-electron bolometer (HEB) mixers and a wealth of impressive experimental results, there has not been much progress in understanding the microscopic physical mechanisms that govern their behavior in heterodyne operation. The HEB, being a superconducting microbridge contacted by normal conducting pads, is operated in a resistive state that is induced by a combination of dc dissipation and absorption of radiation produced by a local oscillator (LO). Heterodyne mixing occurs when a second (small) RF signal is applied, leading to a modulation of the dissipated power at the intermediate frequency (IF), and consequently, to a modulation of the resistance [see, for example, Fig. 1(a)]. It is generally believed that the resistive state of the device in heterodyne operation is related to the dc superconducting transition of the device, in which case, one speaks of a transition-edge detector.[1,2] Recently, it has been shown that the dc resistive behavior at bath temperatures close to the critical temperature T_c is fully determined by the presence of the normal conducting contacts.[3] The conclusion of this study was that the dc transition is only related to the response of the bolometer when the device is operated under the conditions of a bath temperature close to T_c and low current or voltage bias conditions. At lower temperatures, where the device is operated in practice, the resistive state of the microbridge is created by a large current density j and irradiation with LO power. Here, we develop a physical picture that describes the resistance of the device under these conditions and we show how this leads to renewed insight into the mixing principle of HEB's.

Figure 1(b) shows the typical lay out of the microbridge. The contact pads are usually bilayers of a normal metal and a thin superconducting layer, which is also used for the microbridge itself. The contacts are superconducting because the bath temperature T_b in heterodyne experiments is much lower than the (reduced) critical temperature of the contacts.[3] If a dc current is sent through the bridge in combination with irradiation by LO power, a resistive state will develop as soon as the critical current density is exceeded. The contacts remain superconducting, because the current density there is much lower. This is analogous to the situation described by Skocpol, Beasley, and Tinkham, who studied electrical behavior of microbridges with contact pads consisting of the same material.[4] They found that, at low temperatures and high current density, the resistive behavior is dominated by the formation of a normal conducting hotspot, of which the length increases with increasing dissipation.[5] Here, we use the same reasoning to interpret the mixing behavior in HEB's, where, in contrast to Ref. 4, we assume only heating of the electron gas.[6] The *electronic* hotspot is formed due to a combination of heating by dc and LO power. Modulation of the dissipated power in the microbridge by the application of a weak RF signal with a slightly different frequency, modulates the length of the hotspot. As a consequence, the resistance of the microbridge of the device is modulated. In other words, the response of the device is due to a normal hotspot, of which the length oscillates at the intermediate frequency. We call this *hotspot mixing*.[7] Note that in this

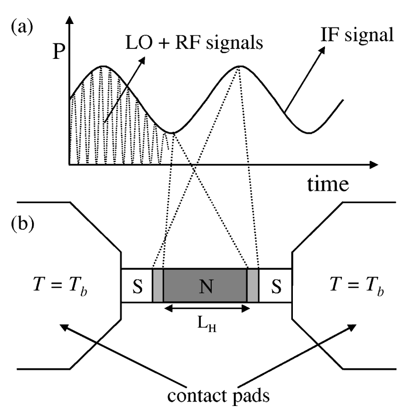

FIG. 1. (a) Absorbed LO and RF power in the superconducting microbridge as a function of time. The slight difference in their frequencies results in a beating of the power at the IF. (b) Top view of the device. As a consequence of the modulation of the dissipated power, the length of the hotspot, and thus the resistance of the microbridge, oscillates at the IF. The N and S regions refer to the normal conducting (hotspot) and superconducting parts, respectively.

[a)]Electronic mail: wilms@phys.rug.nl

situation the change of the resistance has nothing to do with the superconducting transition of the microbridge at T_c. In what follows we will present a model which allows a calculation of the temperature profile and of the pumped $I(V)$ curves of a HEB within the hotspot concept. Also, we describe in some detail the implications of the model with respect to important device parameters, such as the dc voltage responsivity S_0 and the mixer conversion efficiency η_M.

We consider the one-dimensional heat flow in a current-biased superconducting HEB, irradiated with LO power, and with an electronic hotspot centered around its midpoint. Inside the hotspot we get

$$-K\frac{d^2T}{dx^2}+\frac{c_e}{\tau_{e-ph}}(T-T_b)=j^2\rho+p_{\mathrm{LO}}, \tag{1}$$

whereas outside the hotspot we have

$$-K\frac{d^2T}{dx^2}+\frac{c_e}{\tau_{e-ph}}(T-T_b)=p_{\mathrm{LO}}. \tag{2}$$

Here, K is the thermal conductivity, T is the electron temperature,[8] c_e is the electronic heat capacity, τ_{e-ph} is the electron–phonon interaction time, ρ is the normal state resistivity of the microbridge, and p_{LO} is the LO power per unit volume.

A number of assumptions have been made in these equations to allow an analytical solution to the problem. First, we take K to be independent of temperature and equal in the superconducting and normal parts. In reality, the thermal conductivity is a function of the temperature. In the normal region this is described via the Wiedemann–Franz law, whereas in the superconducting parts the decrease in the quasiparticle density with decreasing temperature decreases the thermal conductivity. Second, the cooling of hot electrons to the phonons is taken to be linear in temperature, although empirically it is found to be proportional to $(T_e^4-T_b^4)$.[9] The excited phonons are assumed to escape easily to the substrate, so that the phonon temperature in the microbridge remains at the bath temperature T_b.[10] Also, we assume that LO power absorption is homogeneous along the bridge, which is true if the radiation frequency is above the gap frequency of the superconductor. Direct current dissipation only occurs inside the hotspot. Finally, we ignore nonequilibrium effects in the superconducting parts, which might produce additional resistive behavior.[3]

To solve the equations, we require that the temperature at the ends of the microbridge equals T_b, and the temperature at the boundary of the hotspot is T_c. Matching of $K(dT/dx)$ at the hotspot interface yields the current density that is required to sustain the self-consistent solution as a function of the length of the hotspot and the LO power density. It is useful to introduce a thermal healing length in the analysis, which is the ratio of heat conduction in the microbridge and heat transfer to the phonons. It is given by

$$\lambda_{\mathrm{th}}=\sqrt{\frac{K\tau_{e-ph}}{c_e}}=\sqrt{D\tau_{e-ph}}, \tag{3}$$

where D is the diffusion constant. Electron–phonon relaxation is the dominant heat transport mechanism if the length of the microbridge $L_b>\lambda_{\mathrm{th}}$ (phonon-cooled HEB[1]), whereas diffusion to the contacts dominates if $L_b<\lambda_{\mathrm{th}}$ (diffusion-cooled HEB[2]). Although our model applies in principle to both types, we focus our calculations here on diffusion-cooled devices.

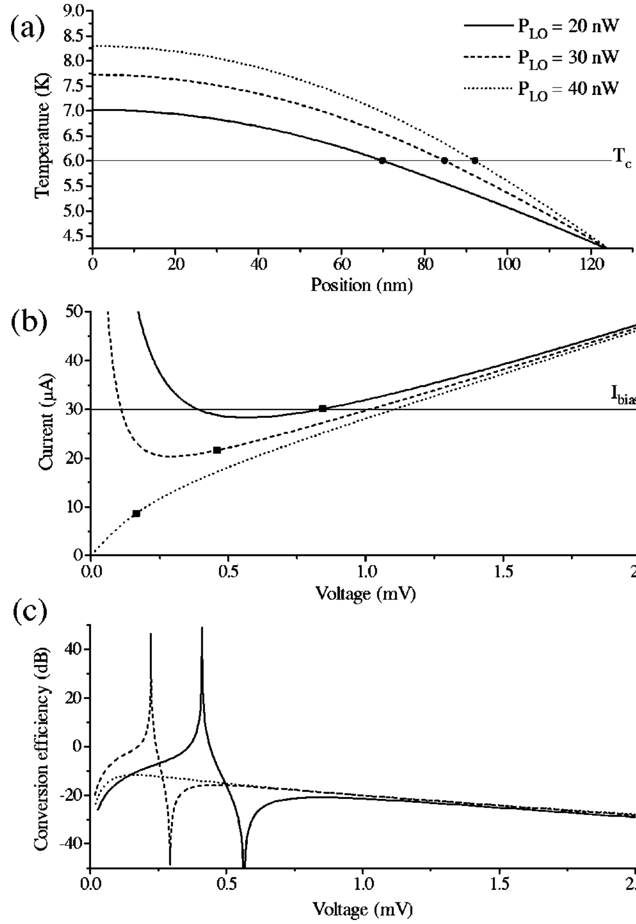

FIG. 2. (a) Temperature profile of a 250 nm long Nb microbridge under different levels of LO power, a bath temperature of 4.2 K, and a constant current I_{bias} of 30 μA. The dots indicate the boundary of the hotspot. (b) Pumped $I(V)$ characteristics of the microbridge. The black squares indicate the bias points where an optimum conversion is predicted. (c) SSB conversion efficiency as a function of bias voltage. The values of the optimum conversion are −21.0 dB (20 nW), −15.9 dB (30 nW), and −11.7 dB (40 nW).

Figure 2(a) shows the calculated temperature profile of a Nb microbridge for different levels of LO power, a constant current of 30 μA, and a bath temperature of 4.2 K. We take $T_c=6$ K, which is typically observed for a 10 nm thick Nb film.[3] The length of the microbridge is 250 nm and its normal state resistance is 50 Ω. For a Nb microbridge, with $D=1.6\,\mathrm{cm}^2/\mathrm{s}$ (Ref. 3) and $\tau_{e-ph}\approx 1$ ns,[9] the thermal healing length is ~400 nm. As a consequence, diffusion cooling dominates, since $L_b<\lambda_{\mathrm{th}}$. In Fig. 2(a), it can be seen that increasing the LO power indeed leads to an increase of the length of the hotspot, marked by the crossing points for $T=T_c$, and thus, to an increase of the resistance of the device. Note that the temperature in the center of the microbridge can be much larger than T_c, depending strongly on the bias conditions. Figure 2(b) shows the corresponding pumped $I(V)$ curves, from which it is clearly seen how a change in LO power results in a change in the voltage across the device in a current-bias situation. A remarkable feature in the $I(V)$ characteristics is the change from negative to positive differential resistance at low voltages with increasing LO power. This can be understood as follows: at low voltage and without applied LO power the dc power needed to sustain the hotspot changes slowly with decreasing voltage.[4] As a result, the current and the voltage are inversely proportional to each other. With increasing LO power, the required dc power decreases. At the point where the LO power alone is large enough to create the hotspot, the sign of the differential resistance changes. At large voltages, the $I(V)$ behavior is quasi-Ohmic. In this case the hotspot boundaries reach the end of the microbridge and the resistance approaches the normal state resistance of the bridge.

An important figure of merit of bolometers is the dc voltage responsivity S_0, defined as the change in voltage drop per watt of absorbed signal power P across the device.[11] Here, we define the responsivity as

$$S_0 = I\left(\frac{dR}{dP}\right) = j\rho\left(\frac{dL_H}{dP}\right). \tag{4}$$

Within the hotspot concept and for a given material, the parameter to be optimized for high sensitivity is dL_H/dP, i.e., the change in length of the hotspot due to a change in absorbed radiation power. With the expression for S_0, we calculate the zero-frequency single-side band (SSB) conversion efficiency η_M of the corresponding mixer for the case in which it is coupled to a load with impedance Z_L. We use[1]

$$\eta_M = \frac{2S_0^2 P_{\mathrm{LO}} Z_L}{(Z_L + Z_B)^2}, \tag{5}$$

where Z_B is the output impedance of the device and is equal to the differential resistance dV/dI in the operating point. We have calculated the conversion as a function of bias voltage for different levels of the LO power density for the case $Z_L = 50\ \Omega$. The result of the calculation is shown in Fig. 2(c). From Eq. (5), it is obvious that the conversion efficiency diverges at the bias point where $Z_B = dV/dI = -Z_L$. In practice, however, due to the bias circuit, it is often hard to find a stable bias point in the negative differential resistance region. Obviously, $\eta_M \to 0$ when $dV/dI \to \infty$. Optimum bias points for conversion in the positive differential regime are indicated in Fig. 2(b). The values we find are comparable in magnitude to values found in heterodyne experiments using a similar device.[12] The SSB conversion efficiency in these experiments was estimated to be -22 dB at $T_b = 4.3$ K and -14.4 dB at $T_b = 2.2$ K. The best response was measured at a bias point slightly above the point where the differential resistance becomes infinite (the ''drop-back'' point), which is consistent with the predictions of our model. Moreover, a clear indication of hotspot formation in these experiments is the observation of hysteresis in the current-biased and pumped $I(V)$ characteristic.[4] Note that in our analysis we did not include the effects of electrothermal feedback in the IF circuit, which might have a large effect on the device performance in practice.

In summary, we propose a HEB mixing mechanism in terms of an electronic hotspot, of which the length oscillates at the intermediate frequency. On the basis of a simple model, we are able to calculate the unpumped and pumped $I(V)$ characteristics and the conversion efficiency. An open question at this time is the noise temperature of the mixer, taking into account the effect of a temperature profile as well as the fact that parts of the microbridge are in a superconducting state, and hence, do not contribute to the noise. This will most likely lead to new predictions for the ultimate noise performance of HEB mixers and can be relevant for future technological developments and the design of a fully optimized detector.

P.A.J. de Korte is acknowledged for helpful discussions. This work is supported by the European Space Agency (ESA) under Contract No. 11738/95/NL/PB and by the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO) through the Stichting voor Technische Wetenschappen (STW).

[1] E. M. Gershenzon, G. N. Gol'tsman, I. G. Gogidze, Y. P. Gusev, A. I. Elant'ev, B. S. Karasik, and A. D. Semenov, Sov. Phys. Supercond. **3**, 1582 (1990).
[2] D. E. Prober, Appl. Phys. Lett. **62**, 2119 (1993).
[3] D. Wilms Floet, J. J. A. Baselmans, T. M. Klapwijk, and J. R. Gao, Appl. Phys. Lett. **73**, 2826 (1998); D. Wilms Floet, J. J. A. Baselmans, J. R. Gao, and T. M. Klapwijk, Proceedings of the Ninth International Symposium Space Terahertz Technology, Jet Propulsion Laboratory, Pasadena, 17–19 March 1998, pp. 63–72.
[4] W. J. Skocpol, M. R. Beasley, and M. Tinkham, J. Appl. Phys. **45**, 4054 (1974).
[5] Josephson coupling between the superconducting banks only plays a role at temperatures very close to T_c. Here, we are interested in the resistive behavior at temperatures well below T_c and we assume that the effective coherence length is much smaller than the dimensions of the microbridge.
[6] The potential importance of hotspots in the current–voltage behavior of HEB's was already recognized by H. F. Merkel *et al.* (Proceedings of the Ninth International Symposium on Space Terahertz Technology, Jet Propulsion Laboratory, Pasadena, March 17–19, 1998, pp. 81–97), whereas the concept of an electronic hotspot is already implicit in Stuivinga *et al.*, J. Low Temp. Phys. **53**, 673 (1983).
[7] Bolometric mixing in point contacts and microbridges can also be due to the modulation of the Josephson current as the result of the modulated electron temperature; see M. Tinkham, M. Octavio, and W. J. Skocpol, J. Appl. Phys. **48**, 1311 (1977). Here, we have no Josephson current, but only normal currents through a conductor of variable length.
[8] Formally, one can only speak of an effective temperature on length scales larger than the inelastic scattering length of the electrons. Here, we neglect the effects of the nonequilibrium distribution of the electrons and assume that an effective temperature can be attributed to each position in the bridge.
[9] E. M. Gershenzon, M. E. Gershenzon, G. N. Gol'tsman, A. M. Lyul'kin, A. D. Semenov, and A. V. Sergeev, Sov. Phys. JETP **70**, 505 (1990).
[10] It is also possible that the heat transfer within the microbridge is limited by the Kapitza resistance between the film and the substrate. In that case, the phonons in the microbridge might heat up to a temperature higher than T_b.
[11] P. L. Richards, J. Appl. Phys. **76**, 1 (1994).
[12] A. Skalare, W. R. McGrath, B. Bumble, H. G. LeDuc, P. J. Burke, A. A. Verheijen, R. J. Schoelkopf, and D. E. Prober, Appl. Phys. Lett. **68**, 1558 (1996).