Large bandwidth and low noise in a diffusion-cooled hot-electron bolometer mixer

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Heterodyne measurements have been made at 533 GHz using a novel superconducting hot-electron bolometer in a waveguide mixer. The bolometer is a 0.3 μm long niobium microbridge with a superconducting transition temperature of 5 K. The short length ensures that electron diffusion dominates over electron-phonon interactions as the electron cooling mechanism, which should allow heterodyne detection with intermediate frequencies (if) of several GHz. A *Y*-factor response of 1.15 dB has been obtained at an if of 1.4 GHz with 77 and 295 K loads, indicating a receiver noise temperature of 650 K DSB. The −3 dB rolloff in the if response occurs at 1.7 GHz. © *1996 American Institute of Physics.* [S0003-6951(96)03911-7]

Bolometers have been used occasionally over the years as heterodyne detectors due to their high sensitivity, and their ability to operate at submillimeter and far-infrared wavelengths.[1,2] Bolometers are simple square-law or total-power detectors. There is no instantaneous response at the signal frequency (rf) as with electronic mixers such as Schottky diodes or SIS tunnel junctions, and there is no harmonic response. The principal disadvantage of a bolometer mixer is the long thermal response time τ_{th}, which limits the intermediate frequency (if) to low values, usually of order MHz for a conventional semiconductor bolometer. This is too low to be useful for most molecular line spectroscopy applications in radioastronomy, atmospheric chemistry, and planetary science.

Recently, however, a novel superconductive transition-edge bolometer has been proposed which is both fast and sensitive.[3] It has a thermal response time as short as several 10's of picoseconds, leading to a rolloff in the if response of several GHz, which is high enough for practical heterodyne applications. This bolometer mixer should operate well to rf frequencies of many THz, since there is no superconducting energy gap limitation as in an SIS mixer. In fact, rf power is absorbed more uniformly above the superconductive energy gap frequency. The mixer noise temperature can be very low: a few times the quantum limit. Very low local oscillator (LO) power is required: ≈20 nW for a Nb device. This is comparable to the requirements for a superconductor-insulator-superconductor (SIS) mixer and is an important issue at high submillimeter wave frequencies where LO power is difficult to generate. The rf impedance of the device is essentially resistive and is determined by the geometry of the film, which greatly simplifies the rf circuit design. Unlike a Schottky diode or SIS tunnel junction, there are no parasitic reactances to tune out. The real rf resistance of the bolometer should be independent of frequency from about the energy gap frequency up to a frequency corresponding to the inverse electron-electron elastic scattering time, which is ~160 THz for a thin Nb film.[3]

Here we present the first demonstration of a heterodyne bolometer mixer with both low noise and a large if bandwidth operating at 533 GHz. Figure 1 shows the geometry of the device, which consists of a submicron-length strip (microbridge) of Nb between two normal metal gold contacts. It is important that the film be very thin, ≤10 nm, and therefore in the "dirty limit." Such dirty limit films have a very high elastic scattering rate due to surface and bulk scattering and therefore a short electron mean free path. It has been found for such films that the electron-electron interaction is enhanced, resulting in a short electron-electron interaction time τ_{ee}, and the electron-phonon interaction is weakened.[4] Thus, when absorbing rf power, the electrons heat up relative to the lattice temperature. The electrical resistance in the film depends on the electron temperature; such a device is known as a "hot-electron" bolometer. Since only the electrons are heated, the heat capacity C can be very small, especially for a submicron-sized device.

A high thermal conductance G between the electrons and the "bath" and therefore an overall short thermal relaxation time $\tau = C/G$ is required for a high if. The unique feature of this device is that is uses the rapid *diffusion* of hot electrons out of the microbridge into the normal metal as the cooling mechanism. In order for diffusion to dominate over electron-phonon interactions,[4] it is necessary for the microbridge to be short; typically less than 1 μm for thin Nb films.

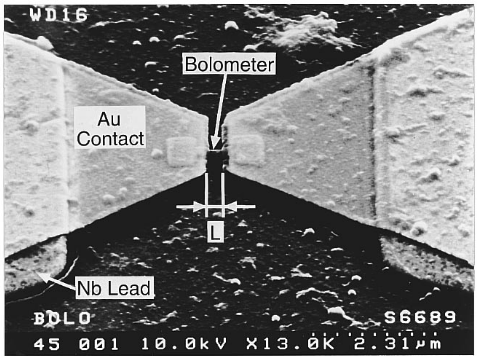

FIG. 1. SEM photo of the diffusion-cooled bolometer.

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The appropriate bridge length L is given by $\sim 2\cdot\sqrt{D\cdot\tau_{ee}}$, where D is the diffusion constant. When an electron absorbs energy from an rf photon, it shares its energy in a time τ_{ee}. The resulting hot electrons diffuse a distance $\sim L/2$ in either direction, at which point they encounter a normal metal heat sink. The thermal conductance is determined through the Wiedemann–Franz relation by the total resistance R_N of the microbridge (see Ref. 5 for a more detailed discussion of the device operation). Similar devices which rely on an electron-phonon cooling mechanism[4,6] have recently achieved an intermediate frequency rolloff as high as 1 GHz, using a thin niobium nitride film.[7]

The bolometer used in the receiver measurements consists of a 0.14 μm wide by 0.27 μm long by 10 nm thick strip of Nb on a quartz substrate. The length is defined by the gap between the contacting gold pads (see Fig. 1). The thick Nb leads form the coupling probe and rf choke filter for the waveguide mixer mount. The device was passivated by 40 nm of SiO. This device has a transition temperature $T_c = 5$ K, the width of the transition is $\Delta T_c \approx 1$ K, and the normal resistance is $R_N = 20\ \Omega$. For these very thin films the sheet resistance is higher and the T_C is lower than the bulk values.

The bolometer chip was mounted into a 547 GHz two-tuner waveguide mixer block [8,9] which was cooled to 2.2 K in a vacuum cryostat. A multiplier driven by a Gunn oscillator generated the local oscillator power at 533 GHz. A cooled high electron mobility transistor (HEMT) amplifier with an isolator was used as the first stage in the if amplifier chain, which operated at 1.4 GHz with a total if noise temperature of 6 K. A 320 MHz bandpass filter was used to limit the if bandwidth. The receiver sensitivity was determined through Y-factor measurements with 295 and 77 K blackbody loads in the signal beam path outside the cryostat. Figure 2 shows the best Y-factor response achieved after adjusting the waveguide backshort and E-plane tuner for best coupling of the LO, and optimizing the LO power. The best response is in the resistive branch of the current-voltage (I-V) curve at a bias voltage just above where the device switches back into the low-resistance state (the bias circuit would not allow for a stable bias in the negative resistance region of the I-V curve). The largest Y-factor was 1.15 ± 0.01 dB, corresponding to a double sideband (DSB) receiver noise temperature of 650 K.

In a separate measurement, the noise temperature and gain of the if system were accurately determined by connecting a temperature-controlled 50 Ω termination in place of the mixer. Using this calibration, it is possible to estimate the conversion efficiency η and noise temperature T_m of the bolometer mixer (including diplexer losses and contributions from the warm and cold optics). This gives $\eta \approx -11.4$ dB (DSB) and $T_m \approx 560$ K (DSB).

The receiver response was also measured at 4.3 K yielding a Y-factor of 0.3 dB which corresponds to a receiver noise temperature of about 3000 K (DSB) and a conversion efficiency of -19 dB (DSB). At this higher operating temperature the optimal amount of LO and dc power that will bring the electron temperature up to T_c is lower. The conversion efficiency will therefore also be lower since it depends on these power levels.[10] The increase in noise is likely due to the poorer conversion efficiency, and not to an increase in mixer output noise. This is dominated by fluctuations in the electron temperature,[11] which is always near T_c. This explanation is supported by the fact that the increase in noise correlates well with the decrease in conversion efficiency.

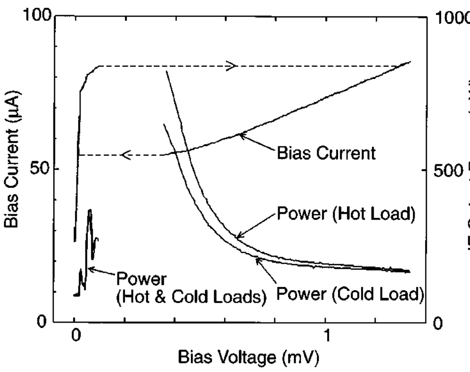

FIG. 2. The current–voltage ($I-V$) curve for the bolometer with local oscillator power applied. The dashed lines show the regions in which switching occurs. The device resistance is negative below about 0.4 mV. The normal resistance R_N is 20 Ω. The if output power is shown for both a hot (295 K) and a cold (77 K) load in the receiver signal path..

An important issue for a bolometer mixer is the response due to the broadband thermal radiation from the 295 K calibration load, which could heat the lattice as well as saturate the mixer. To ensure that we were correctly measuring the intrinsic heterodyne properties, several tests were made to check for nonheterodyne contributions to the response. Switching between loads in the signal path with LO power applied and with both loads at 295 K gave no response, which shows that the mixer response is not due to standing waves in the local oscillator path. Switching between 295 and 77 K loads without LO power did not give any output power response. The same switching with optimum LO power applied did not shift the bias voltage of the device measurably (the measurement sensitivity was 2 μV) with the bolometer current-biased at dc, indicating that the measured mixer response was not a result of a bias point shift due to heating from the hot and cold loads.

In a separate measurement, an additional Gunn oscillator was connected to the multiplier, which thereby generated both power at the local oscillator frequency and a weak signal that could be used as a monochromatic source for mixer experiments. The if output was connected to a spectrum analyzer. Measurements were made with the mixer block at 4.3 and 2.2 K. In both cases the mixer output did indeed contain a distinct monochromatic signal, which could be tuned over the whole available 1–2 GHz if band by adjusting the frequencies of the two Gunn oscillators. A measurement at 2.2 K showed that the difference in if output power when switching between a hot and a cold blackbody load in the receiver beam showed the same bias voltage dependence as did the output power due to the monochromatic signal source. This fact further supports that the measured Y-factor is due to a heterodyne response. Additionally, a superconducting magnet inside the cryostat was used to apply a magnetic field of $\sim$400 G to the bolometer, but was observed to have no effect on the monochromatic if output power to within the accuracy of this measurement (0.2 dB). This suggests that none of the response was due to Josephson effect mixing in this micro-

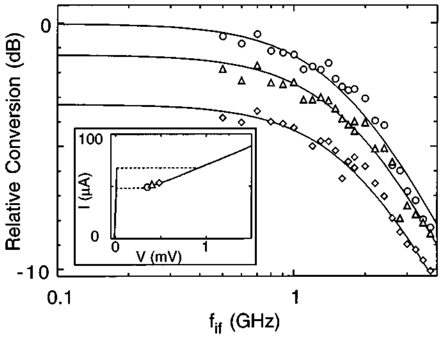

FIG. 3. The mixer conversion as a function of intermediate frequency for three different bias conditions. These data are normalized to the conversion at low if for a bias voltage of 0.35 mV. The bias voltages and the rolloff frequencies of the fitted theoretical curves are (○): 0.35 mV, 1.7 GHz; (△): 0.40 mV, 1.8 GHz; (◇): 0.48 mV, 1.9 GHz. The three dc bias points are marked in the $I-V$ curve in the inset.

bridge, and that the rf heating was generally uniform with no hotspots or superconductor-normal boundaries.[12]

An important property of a bolometer mixer is the if dependence of the conversion efficiency, which is set by the thermal response time. Due to significiant output power variations with frequency in the multiplier/two-Gunn source, we chose to determine this dependence with a broadband blackbody rf signal source and with a spectrum analyzer used as a tunable 1 MHz filter after the if amplifier chain.[13] The if system of the receiver was reconfigured with a broadband field effect transistor (FET) amplifier that was cooled to 77 K in place of the HEMT amplifier and isolator. The measurement was done by switching between a 295 and a 77 K load in the receiver beam, thereby varying the receiver if output power. Due to variations in the spectrum analyzer response, particular care was taken in the gain calibration of the if chain.[13] The receiver was tuned to maximize the LO coupling to the bolometer in the same way as for the Y-factor measurement described earlier, but the applied LO power level was slightly higher. In a separate Y-factor measurement this yielded a receiver noise temperature of 660 K (DSB).

Figure 3 shows the relative conversion efficiency versus intermediate frequency (f_{if}) at 3 bias points above the dropback voltage. A fitted curve with the expected frequency dependence[1] $[1+(f_{\mathrm{if}}/f_{\mathrm{rolloff}})^2]^{-1}$ is also shown, where f_{rolloff} is the intermediate frequency at which the conversion efficiency drops by 3 dB. The rolloff in Fig. 3 occurs at 1.7–1.9 GHz. As can be seen, f_{rolloff} does not increase as quickly as the conversion efficiency decreases with bias voltage. This supports the prediction of no fixed "gain-bandwidth" product for this device.[10]

The measured rolloff frequency allows the actual effective thermal conductance G_s of the bolometer to be calculated from $f_{\mathrm{rolloff}}=1/(2\pi\tau_{\mathrm{th}})$ where $\tau_{\mathrm{th}}=C/G_s$. For this device, this gives $G_s\approx 15$ nW/K, which compares well with dc measurements which we have previously reported for similar microbridges.[14] The LO power (P_{LO}) applied to the bolometer mixer can then be approximated using $P_{\mathrm{LO}}+P_{\mathrm{dc}}\approx G'*(T_c^2-T_b^2)/(2T_c)$ where $T_c\approx 5$ K, $T_b\approx 2.2$ K is the mixer physical temperature, P_{dc} is the dc dissipated power, and $G'\approx G_s$. This yields $P_{\mathrm{LO}}\approx 15$ nW which is consistent with the expected low LO power requirements for this device.

A simulation of the bolometer mixer that takes into account the temperature profile in the device has been made using a finite difference method. The heat diffusion in the bolometer is assumed to follow the Wiedemann–Franz law, where the thermal conductivity is proportional to temperature. The proportionality constant was adjusted to agree with dc measurements.[14] The calculated mixer conversion efficiency at low if is 6.3 dB (DSB), and the −3 dB rolloff occurs at 1.3 GHz. These values are in reasonable agreement with the measured results, and therefore support the diffusion model for this bolometer.

In summary, a novel transition-edge bolometer mixer that uses diffusion as a cooling mechanism for hot electrons has been demonstrated at 533 GHz. This mixer provides very low heterodyne receiver noise temperatures, with high intermediate frequencies. The −3 dB if response extends to 1.7 GHz. The diffusion-cooled bolometer mixer is expected to perform well up to at least several THz with little change in performance. It is thus an attractive alternative to less-sensitive Schottky mixers at very high (>1 THz) submillimeter wave frequencies.

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