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Nb–Au bilayer hot-electron bolometers for low-noise THz heterodyne detection

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The sensitivity of present Nb diffusion-cooled hot-electron bolometer (HEB) mixers is not quantum limited, and can be improved by reducing the superconducting transition temperature T_C. Lowering T_C reduces thermal fluctuations, resulting in a decrease of the mixer noise temperature T_M. However, lower T_C mixers have reduced dynamic range and saturate more easily due to background noise. We present 30 GHz microwave measurements on a bilayer HEB system, Nb–Au, in which T_C can be tuned with Au layer thickness to obtain the maximum sensitivity for a given noise background. These measurements are intended as a guide for the optimization of THz mixers. Using a Nb–Au mixer with $T_C = 1.6$ K, we obtain $T_M = 50$ K with 2 nW of local oscillator (LO) power. Good mixer performance is observed over a wide range of LO power and bias voltage and such a device should not exhibit saturation in a THz receiver.
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Spectroscopy of molecular vibrational and rotational line emissions in the submillimeter and terahertz bands provides a powerful tool for astronomers studying the composition and evolution of distant objects.[1] Low-noise terahertz heterodyne detectors are also employed for terrestrial remote sensing. Superconducting hot-electron bolometer (HEB) mixers are currently being developed and tested for such ground-based and space-based THz receivers, to provide improved sensitivity.[2,3] This letter presents measurements of a diffusion-cooled HEB based on a composite film, Nb–Au, with a tunable transition temperature T_C between 1 and 5 K. T_C is reduced by the proximity effect of the Au film. This Nb–Au HEB can provide an improvement in sensitivity over Nb mixers ($T_C \approx 6$ K).[4] It should also be compatible with practical levels of background noise in THz receivers, unlike other low T_C HEB mixers (e.g., Al, $T_C \approx 1.0$ K) which are prone to saturation effects.

The HEB mixer consists of a thin-film superconducting nanobridge between two thick, normal (nonsuperconducting) contacts; see Fig. 1. The signal at frequency f_s combines with a local oscillator (LO) to produce a temperature modulation at the intermediate frequency $f_{\mathrm{IF}} = |f_s - f_{\mathrm{LO}}|$. HEB mixers, both diffusion-cooled (Nb)[5] and phonon-cooled (NbN),[6] have demonstrated low double-side-band mixer noise temperature, $T_M \approx 2000$ K(DSB) above 2 THz, lower than Schottky diode mixers. They also require much less LO power. The HEB mixer has an upper frequency limit of maybe 100 THz,[7] much higher than demonstrated for SIS mixers, which are currently limited to $f_s \leqslant 1.4$ THz.[8]

Improved performance of diffusion-cooled HEB mixers should be observed in devices with lower transition temperature than Nb. This is because the dominant noise is due to thermal fluctuations, which scale as T_C (Refs. 7 and 9), plus quantum noise, which gives $T_M > T_Q = hf_s/k_B$; k_B is Boltzmann's constant. Present HEB devices have mixer noise that far exceeds T_Q, and a reduction of T_M by lowering T_C is achievable, and has been observed in past microwave tests of Al HEB mixers.[10] Improvements in noise temperature can be made without compromising IF bandwidth for diffusion-cooled HEBs because the fast thermal time constant τ_{th} which gives rise to a large IF bandwidth is based on electron diffusion, which is independent of T_C. For phonon-cooled HEBs, in contrast, the IF bandwidth would be dramatically reduced if T_C were lowered, since $\tau_{\mathrm{th}} \approx T_C^{-p}$ for electron–phonon coupling, with $p = 2-4$.[11] Lower T_C mixers in general are more prone to saturation both at the input and output ports. THz measurements have shown that Al HEBs saturate due to background photons.[12] We have shown that the limited dynamic range of Al HEBs, seen in microwave mixing experiments at 30 GHz, does indeed predict these saturation effects.[10,14] Thus, 30 GHz tests can be used to initially qualify or disqualify a given HEB candidate. The dynamic range depends on the material system, as well as T_C. We demonstrate that reduced mixer noise and reasonably large

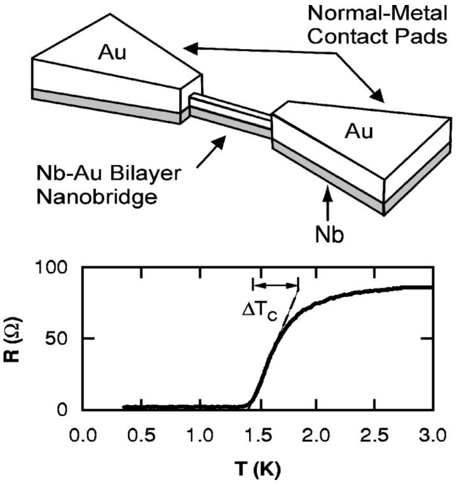

FIG. 1. Nb–Au HEB device geometry (top) and R(T) characteristic (bottom).

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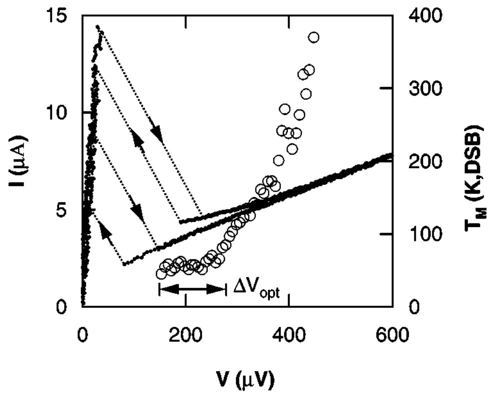

FIG. 2. I (lines) and T_M (open circles) vs bias voltage V for the the Nb–Au HEB. The two hysteretic $I-V$ curves correspond to $P_{\mathrm{LO}}=0$ (upper curve) and $P_{\mathrm{LO}}=2$ nW.

dynamic range are achieved with a Nb–Au bilayer (proximity effect) HEB with $T_C=1.6$ K. This device should not show significant saturation effects in the THz range. In modern THz observatories, typical background noise temperatures are <100 K.[13]

Microwave measurements were used to study HEB mixer properties to achieve an environment with low background noise. These measurements are intended to investigate the optimization of HEB mixers and to provide a qualitative guide for development of future THz receivers. Our apparatus is a ^{3}He cryostat with $T=0.22$ K, with coaxial inputs for signals up to 40 GHz. Calibrated cryogenic attenuators and a cryogenic IF amplifier and isolator were used to ensure that background rf power was negligible, including that from room temperature emissions. We tested the HEB dynamic range by adding a controlled level of background power. In Fig. 1 we show the resistive transition for a Nb–Au mixer in which the nanobridge has a length $L=0.48$ μm and is a composite of 10 nm of Au and 10 nm of Nb. In Fig. 2 we present its current–voltage characteristic with and without applied LO power. The critical current is $I_C=14$ μA with no LO power, and 9 μA with $P_{\mathrm{LO}}=2$ nW applied. This optimum LO power yields a lowest value of $T_M=50$ K(DSB), calculated by dividing the measured output noise temperature by twice the measured single sideband conversion efficiency, $\eta=-14.5$ dB at $f_{\mathrm{IF}}=1.0$ GHz; $T_M=T_{\mathrm{out}}/2\eta$. The conversion efficiency at $f_{\mathrm{IF}}=0$ is $\eta=-12.5$ dB. The IF bandwidth is measured to be 1.2 GHz, consistent with predictions based on the measured diffusion constant of the nanobridge.[14] A significantly larger IF bandwidth can be achieved with a shorter nanobridge.[15]

Background noise can cause saturation at the mixer input or its output, increasing T_M and reducing the conversion efficiency. We find in our measurements that input saturation begins to occur when the background power is $P_{\mathrm{bkgnd}}\approx 0.1P_{\mathrm{LO}}$;[14] we therefore specify a limit of $P_{\mathrm{bkgnd}}\leqslant 0.2P_{\mathrm{LO}}=0.4$ nW for the Nb–Au mixer with $T_C=1.6$ K. With an input bandwidth BW $=300$ GHz, saturation would occur when the background noise temperature is $T_{\mathrm{bkgnd}}>100$ K, with $P_{\mathrm{bkgnd}}=k_B T_{\mathrm{bkgnd}}\cdot \mathrm{BW}$. Waveguide receivers can meet this bandwidth requirement, and this limited bandwidth can also be achieved with quasioptical coupling above 1 THz.[13,16] Quasioptical coupling often is less than 100% efficient, and if the losses occur in cold parts of the receiver, the rf bandwidth could be larger than 300 GHz without significant input saturation.

Output saturation results when background noise is downconverted to the IF band and produces a large voltage swing. The mixer in such a situation samples voltage regions of poor performance. The result is higher mixer noise and lower conversion efficiency than with no background power. The Nb–Au mixer exhibits low T_M over a relatively wide range of operating voltage; $T_M<100$ K over a range in bias voltage $\Delta V_{\mathrm{opt}}=130$ μV. The minimum value of $T_M=50$ K is obtained for $P_{\mathrm{LO}}=2-4$ nW, and $T_M<100$ K for $P_{\mathrm{LO}}=1-7$ nW. For a mixer with a 4 GHz IF bandwidth, we estimate that input noise $T_{\mathrm{bkgnd}}\approx 10\,000$ K would result in output saturation. Thus, the Nb–Au mixer with $T_C=1.6$ K should be unaffected by output saturation. Note, however, that if the operating voltage range were 20 times smaller, as seen for some Al HEBs, saturation would occur for $T_{\mathrm{bkgnd}}\approx 25$ K. In that case, saturation would likely be unavoidable in a THz receiver.

To illustrate the trade-off between sensitivity and saturation for mixers with different T_C, we present in Table I microwave mixing data for various HEBs studied by us: the Nb–Au mixer with $T_C=1.6$ K, a Nb mixer with $T_C=5.5$ K, and an Al mixer with $T_C\approx 1.0$ K. For the Al HEB a field of 0.12 T was applied to suppress the superconductivity in the contacts. Table I shows a number of trends. For Nb and Nb–Au HEBs, we see that both have reasonable conversion efficiency. The mixer noise temperature decreases with T_C by a factor of 3, the ratio of T_C, as expected since the dominant noise at 30 GHz is due to thermal fluctuations. At $f_s\gg 1$ THz, the contribution of quantum noise is significant since $T_Q=48$ K/THz$\cdot f_s$. A reduction in thermal fluctation noise becomes less significant at very high frequencies where T_M is dominated by quantum noise. However, for present applications up to a few THz, the reduced thermal noise in Nb–Au HEBs should result in significantly improved noise performance compared to Nb mixers. Lowering T_C also reduces the LO power. For a diffusion cooled mixer operating at $T\ll T_C$, $P_{\mathrm{LO}}\propto T_C^2$. The LO powers listed in Table I are in reasonable agreement with this prediction. In addition to LO

TABLE I. Mixer properties, measured at $f_{\mathrm{LO}}=30$ GHz. For the Al HEB, T_C is slightly depressed from the bulk value due to the proximity effect of the normal contacts. The data presented have been taken at $f_{\mathrm{IF}}=1.5$ GHz for Nb and Al mixers and at $f_{\mathrm{IF}}=1.0$ GHz for the Nb–Au mixer. HEB resistances above T_C are similar: $R_{\mathrm{Nb}}=110$ Ω; $R_{\mathrm{Nb-Au}}=80$ Ω, and $R_{\mathrm{Al}}=50$ Ω. Here T_M is the minimum mixer noise temperature.

HEB	T_C(K)	I_C(μA)	T_{out}(K)	η(dB)	T_M(K)	ΔV_{opt}(μV)	P_{LO}(nW)
Nb	5.3	100	13	-14	160	200	10
Nb–Au	1.6	14	3	-14.5	47	130	2
Al	≈ 1.0	3	4	-11	25	$\lesssim 10$	0.3

power, a reduction in T_C decreases the operating voltage range, ΔV_{opt}, but should not result in saturation for Nb–Au devices. The Al HEB has the best noise performance, but the voltage range over which this performance is obtained is very small, $\Delta V_{\mathrm{opt}} < 10\ \mu\mathrm{V}$. In Al, this narrow operating voltage range partly results from the long superconducting coherence length.[14] Having such a small range of operating bias voltage will likely cause output saturation and result in the poor performance observed in THz measurements of Al mixers.[12] We have conducted numerical simulations based on the frequency domain model described in Ref. 17. These confirm that Al mixers should indeed have a very narrow operating voltage range. We conclude that Al HEBs are too sensitive to saturation to be used in typical THz applications. Nb and Nb–Au HEBs have a much shorter coherence length, and our simulations show that the operating voltage range is larger and in agreement with observed experimental values.

Our microwave measurements illustrate the trend that reducing T_C reduces thermal fluctuation noise. Although the noise temperature measured at THz frequencies is higher than that observed in microwave measurements, we expect the performance of THz receivers will be significantly improved with the incorporation of Nb–Au devices. Direct measurements are needed to quantify the terahertz performance. Receivers with cooled optics and/or a low background noise can readily utilize such Nb–Au mixers. The small LO power of 2 nW is advantageous for possible coupling with solid-state LO sources at $f_{\mathrm{LO}} > 2$ THz, and for array applications. Last, the HEB transition temperature T_C can be chosen between 1.6 and 5 K by using different Au thicknesses. In this way, the Nb–Au HEB can be designed to accommodate the operating/background conditions of a specific application. Nb or NbN HEBs will be appropriate in an environment with larger background noise.

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