ALUMINUM SUPERCONDUCTING HOT-ELECTRON BOLOMETER MIXERS FOR THz APPLICATIONS

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We report on microwave measurements of superconducting aluminum hot-electron bolometers (Al HEBs). Diffusion-cooled Al HEB mixers are ideal candidates for space-borne and terrestrial remote-sensing applications in the Terahertz frequency range since they are predicted to have small local oscillator (LO) power requirements, intermediate frequency (IF) bandwidths ¤ 10 GHz, and a noise temperature lower than that of Nb and NbN HEBs.[1] Mixer measurements were made at an LO frequency ~30 GHz LO, with an IF in the range 0.1-7.3 GHz. For T < 0.8 K, a magnetic field H=0.1-0.3T was applied to suppress the superconductivity in the contact pads, and partly in the bridge. For a 0.6 ¼m long Al HEB, we measure an IF bandwidth of 4 GHz, a conversion efficiency · = -8dB, and a mixer noise temperature T_m ¤ 4K, DSB (T_{mixer}=$T_{output\ noise}$/2·). These results are shown to be in quantitative agreement with simple theoretical predictions.

I. Introduction

Recent studies on Nb and NbN hot-electron bolometer (HEB) mixers have demonstrated that they are excellent candidates for Terahertz spectroscopy applications.[2-4] For Nb HEB mixers, the largest intermediate frequency (IF) bandwidths are obtained for devices much shorter than the inelastic electron-phonon length. These rely on the out-diffusion of hot electrons from the microbridge into cold reservoirs as the dominant mode of energy relaxation.[5] Diffusion-cooled Nb mixers have demonstrated IF bandwidths up to 10 GHz, with the local oscillator (LO) power needed for optimal operation typically ~ tens of nW at Terahertz frequencies. The noise performance of diffusion-cooled Nb devices is excellent, with an achieved receiver noise temperature T_R=1800K, DSB at 2.5THz. [3]

Recently, HEBs employing superconductors with a lower transition temperature than Nb (T_c ~ 6K) have been proposed.[1] The devices studied here are diffusion-cooled HEBs based on Al, with T_c ~ 1.5 to 2.4K. Improvements in mixer performance are predicted since clean Al films have a lower transition temperature and a higher diffusivity D than Nb films.

We present measurements for Al HEB mixers at microwave frequencies. The frequency of the LO source used is ~ 30 GHz. The primary motivation for studying mixing at microwave frequencies is that much of the device physics relevant to THz mixing can be explored with the simpler microwave measurements. Previous microwave studies of Nb HEBs has been useful in this respect.[2]

We present here predictions for mixer performance of Al HEB[1,2] devices. The IF bandwidth of the HEB mixer can be estimated from the thermal time constant t_{th} of the device. The thermal relaxation rate has a term due to inelastic electron-phonon scattering, and one due to the "out" diffusion rate -- $t_{th}^{-1} = t_{e-ph}^{-1} + t_{diff}^{-1}$. In our devices, electron-phonon scattering is negligible, and the thermal time constant is given by the diffusion time[2]

$$t_{th\approx}\tau_{\delta\iota\phi\phi} = \Lambda^2/\aleph^2\Delta \qquad (1)$$

and the –3dB intermediate frequency rolloff is thus:

$$f_{-3dB} = 1/(2pt_{eff}) = 1/(2pt_{th}). \qquad (2)$$

L is the length of the bolometer. Eq. (1) applies when electro-thermal feedback is small, so that $t_{eff} = t_{th}$.

The higher the diffusivity, the larger the IF bandwidth. Calculations for devices several coherence lengths long indicate that an IF bandwidth ¤ 10 GHz should be attainable.

Al HEBs are also promising since the LO power required for operation is predicted to be lower than that of Nb and NbN mixers. The LO power for a diffusion-cooled device is given by[2,6]

$$P_{LO} = 4£ (T_c^2 - T^2)/R. \qquad (3)$$

where £ = 2.45x10-8 Watt-Ohm/K2 is the Lorenz constant and R the device resistance. At 2.5 THz, for Nb HEBs, P_{LO} ~ 20 nW[3] and P_{LO} ~ 100 nW[7] for NbN phonon-cooled HEBs. The LO power dissipated in the mixer in Al should be ~ 0.2 nW based on scaling of the data obtained for Nb at 20 GHz[2], and ~2nW for THz operation.[8,9]

Though HEB mixer theories for noise are currently under discussion, we discuss here two main thermal noise sources: thermal fluctuation noise and Johnson noise. The contribution of thermal fluctuation noise to the total device noise is proportional to the critical temperature[10], and should thus be smaller in Al devices than in Nb ones. Lowering the T_c of the HEB will similarly result in a decrease of the Johnson noise. Quantum noise, however, must also be considered. A lower bound on the contribution to the mixer noise is T_MQ ≈ hn/k [11].At the microwave frequencies we used, the quantum noise is almost negligible, ~1K. At Terahertz frequencies, the quantum noise limit is not negligible. T_M Q= 120K at 2.5 THz. Since the measured mixer noise of Nb HEBs is much greater than T_MQ, we believe that reducing the two thermal contributions, by use of Al HEBs, will reduce T_M. This should hold true even for more advanced noise theories. The mixer noise temperature at 30 GHz due to thermal sources is predicted to be ~8 K by scaling the best results obtained with Nb at 20 GHz by T_c.

II. Devices and Measurement Setup

The devices consist of a thin, narrow Al microbridge with dimensions d=13-17nm, W=0.1¼m, and L=0.2-1¼m, where d,W, and L are the thickness, width, and length, respectively. Thick contacts consist of a tri-layer of Al, Ti, and Au with thickness ~ 68nm, 28nm, 28nm respectively on top of the thin Al film. The fabrication details can be found in Ref. 12. The device parameters are summarized in Table I.

Device	R_n (W)	L (mm)	ρ(μ Ω-cm)	D (cm^2/s)
A	52	0.6	15	6.0
B	145	0.3	65	2.5
C	260	1.0	36	4.4
D	387	0.6	85	2.9

Table I: Device parameters. Diffusion constant value of devices A and D are measured, while those for B and C are inferred from the resistivity. The device width is 0.1mm. For mixer tests, Tc=1.0K for device A in a magnetic field to 2.4K for device B in zero field.

The superconducting transition temperature of the Al microbridges in zero field ranged from ~ 1.5-2.4 K depending on length and resistivity. The contact pads are a combination of normal and superconducting metals, and have a transition temperature which is lower than that of the microbridge, with $T_{c,contact\ pads}$ ≈ 0.6-1.0K. For tests below $T_{c,contact\ pads}$ a perpendicular magnetic field is applied to suppress the superconductivity in the contact pads.

The devices are mounted on the cold stage of a variable temperature 3He cryostat. The bath temperature was varied from 0.25-1.6K for the mixing experiments, and up to 40K for Johnson noise calibrations and other measurements. A schematic of the measurement setup is shown in Fig. 1.

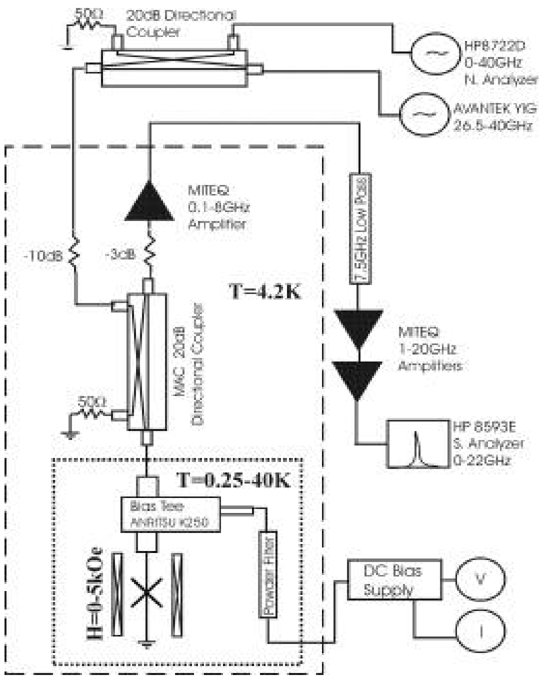

Fig. 1

III. Results

A. IF Bandwidth

The IF bandwidth depends on the bias point used. Measurements reported here are for bias points in the resistive state where conventional HEB mixing models can be applied. The measured IF bandwidth ranged from 1.2-6 GHz. In Fig. 2, a comparison is made between the measured IF bandwidth and the value predicted from a calculation of the diffusion time

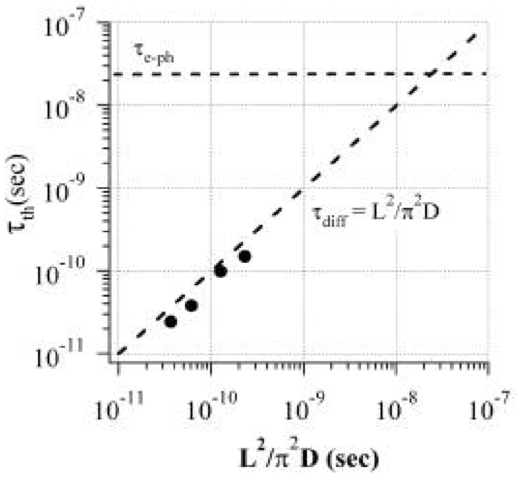

Fig. 2

The bias points considered in determining the IF bandwidth were the ones which gave the maximum conversion efficiency in the resistive state. We can see good agreement with the prediction for a diffusion-cooled mixer.

B. Optimum LO Power

The LO power used in the mixing experiments is in the range of õ 1.0 nW delivered to the mixer block. Values of the conversion efficiency and mixer noise are presented as a function of LO power in Fig. 3. The mixer noise temperature is calculated from the output noise of the device and the conversion efficiency: T_m(DSB)=T_{output}/2h. The LO power needed for optimum conversion efficiency is approximately the same value that gives the best noise performance. Experimentally this is the case since the output noise is slowly varying with bias voltage and thus the dominant factor in determining the voltage dependence of the mixer noise is the conversion efficiency. Measurements of the temperature dependence of the optimum LO power were also made, and are in agreement with the relation presented in Eq. (3).

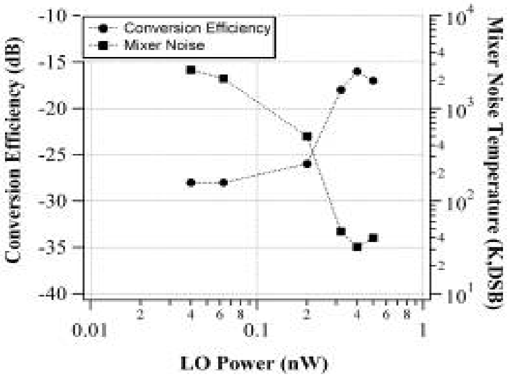

Fig. 3

C. Mixer Noise

In Fig. 4, the dependence of mixer noise and of conversion efficiency on bias voltage is shown for device A, using $T_m=T_{out}/2h$. The minimum of the mixer noise temperature is ~4 K for device A. At the LO frequency used, this is ~ 3 hv/k. The mixer noise temperature with a 20 GHz LO in Nb HEBs was ~ 120 hn/k in the case with a finite critical current, but 33 hn/k when the critical current was fully suppressed by P_{LO}.[6]

This mixer noise temperature is somewhat lower than predicted by simply scaling Nb data at 20 GHz according to T_c. However, in the Nb measurements, there was excess noise, the origin of which was not explained. For the Al HEBs, the total output noise is consistent with thermal fluctuation and Johnson noise contributions with Johnson noise of the magnitude expected for $T \sim T_c$.

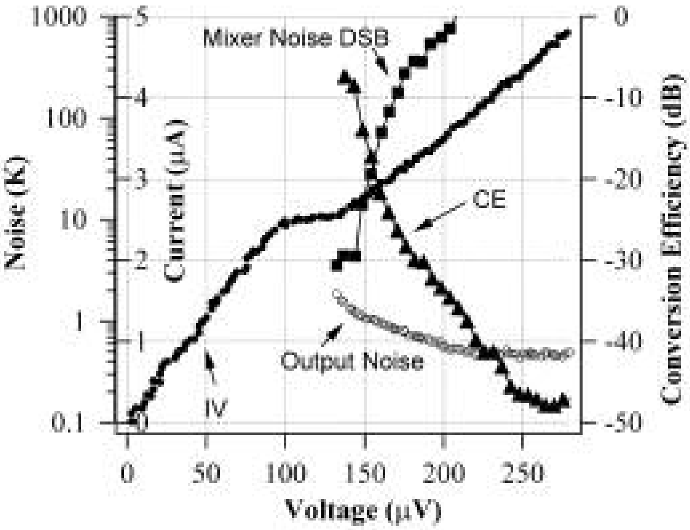

Fig. 4

IV. Conclusions

Results for mixing with Al HEBs at microwave frequencies are very good. The IF signal bandwidth scales with device length and diffusivity as predicted in the diffusion cooling model, Eq. (1). The LO power needed for mixing scales approximately linearly with T_c. The measured mixer noise is somewhat lower than that predicted by scaling Nb HEB results. The measured IF bandwidth and optimum LO power are in good agreement with lumped element predictions.

Currently, a major design issue for space-borne application of HEB mixer receivers is the availability of an appropriate LO source. Molecular lasers are heavy and need high-power sources. Other possibilities at present are photomixer sources and multipliers. A successful traveling-wave THz photomixer has been shown to have an output power of at least ~ 10nW above 1 THz.[13] This is not enough for mixing with Nb HEBs. But our results for the optimum LO power for Al HEB mixers indicate that there is real possibility for integrating a THz Al HEB mixer with such a photomixer.

In actual receivers, saturation effects have to be considered. Since the bias voltage range over which good performance is observed is tens of microvolts, output saturation due to background noise or a large input signal might be an issue. Choosing a smaller mixer bandwidth for situations when high input power is present is a potential solution. Further work is needed to quantify at which power levels saturation effects are significant.

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