Noise and Conversion Efficiency of Aluminum Superconducting Hot-Electron Bolometer Mixer

Irfan Siddiqi, Aleksandr Verevkin, Daniel E. Prober,
Anders Skalare, Boris S. Karasik, William R. McGrath, Pierre Echternach, and Henry G. LeDuc

***Abstract*—We report on microwave measurements of superconducting aluminum hot-electron bolometers (Al HEBs). Diffusion-cooled Al HEB mixers are good candidates for space-borne applications in the Terahertz frequency range since they are predicted to have small local oscillator (LO) power requirements, intermediate frequency (IF) bandwidths $\gtrsim$ 10 GHz, and a noise temperature lower than that of Nb and NbN HEB mixers. Mixer measurements were made at an LO frequency ~30 GHz, with an IF in the range 0.1 to 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 μm long device, we measure an IF bandwidth of 4 GHz, a conversion efficiency η = -8dB, and a mixer noise temperature $T_M \gtrsim$ 4K, DSB ($T_{mixer}=T_{output\ noise}/2\eta$). These results are shown to be in quantitative agreement with simple theoretical predictions.**

Index Terms — **Hot-Electron Bolometer, Mixer, Terahertz Spectroscopy.**

I. INTRODUCTION

Recent studies on Nb and NbN hot-electron bolometer (HEB) mixers have demonstrated that they are excellent candidates for Terahertz spectroscopy applications [1]-[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 cooling [5]. Diffusion-cooled Nb mixers have demonstrated IF bandwidths up to 9 GHz, with the local oscillator (LO) power needed for optimal operation typically a few 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 ($T_c \sim 6K$) have been proposed [1]. The devices studied here are diffusion-cooled HEBs based on Al, with $T_c \sim 1.5$ 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 (f_{LO}~30 GHz). The primary motivation for studying mixing at microwave frequencies is to explore the device physics relevant to THz mixing with the simpler microwave measurements. Previous microwave studies of Nb HEB mixers have been useful in this respect [2].

We present here predictions for mixer performance of Al HEB devices [1], [2]. The IF bandwidth of the HEB mixer can be estimated from the thermal time constant τ_{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 - $\tau_{th}^{-1} = \tau_{e\text{-}ph}^{-1} + \tau_{diff}^{-1}$. In our devices, the electron-phonon scattering rate is negligible, and the thermal time constant is given by the diffusion time [2]

$$\tau_{th} \approx \tau_{diff} = L^2/\pi^2 D, \quad (1)$$

and the −3dB intermediate frequency rolloff is thus:

$$f_{-3dB} = 1/(2\pi\tau_{eff}) = 1/(2\pi\tau_{th}) = \pi D/2L^2. \quad (2)$$

L is the length of the bolometer. Eq. (1) applies when electro-thermal feedback is small, so that $\tau_{eff} = \tau_{th}$ [2].

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]

$$P_{LO} = 4\mathcal{L}(T_c^2 - T^2)/R \quad (3)$$

where $\mathcal{L} = 2.45\times10^{-8}$ Watt-Ohm/K^2 is the Lorenz constant and R the device resistance. At 2.5 THz, for Nb HEBs, $P_{LO} \sim 20$ nW [3] and P_{LO} 100 nW [4],[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].

HEB mixer theories for noise are currently under discussion. We treat 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 [8], and should thus be smaller in Al devices than in Nb ones. Lowering the T_c of the HEB will similarly result in a proportionate decrease of the Johnson noise. Quantum noise, however, must also be considered. A lower bound on the mixer noise is $T_M^Q \approx h\nu/k$ [9]. At the microwave frequencies we used, the quantum noise is

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I. Siddiqi, A. Verevkin, and D. E. Prober are with the Department of Applied Physics, Yale University, New Haven, CT 06520 USA (telephone: 203-432-4129, e-mail:irfan.siddiqi@yale.edu;daniel.prober@yale.edu)

A. Sakalare, B. S. Karasik, W. R. McGrath, P. Echternach, and H. G. LeDuc are with the Jet Propulsion Laboratory, NASA, Pasadena, CA 91109.

TABLE I
DEVICE PARAMETERS

Device	$R_N(\Omega)$	L (μm)	ρ (μΩ-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

Diffusion constant value of devices A ($\xi(0)$=50nm) and D are determined from upper critical field measurements, while those for B and C are inferred from the resistivity. The device width is 0.1μm. For mixer tests, T_c=1.0K for device A in a magnetic field to 2.4K for device D in zero field. Device A has the most desirable characteristics.

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_M^Q, 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 these thermal noise sources is predicted to be ~8 K by scaling according to T_c the best results obtained with Nb at 20 GHz.

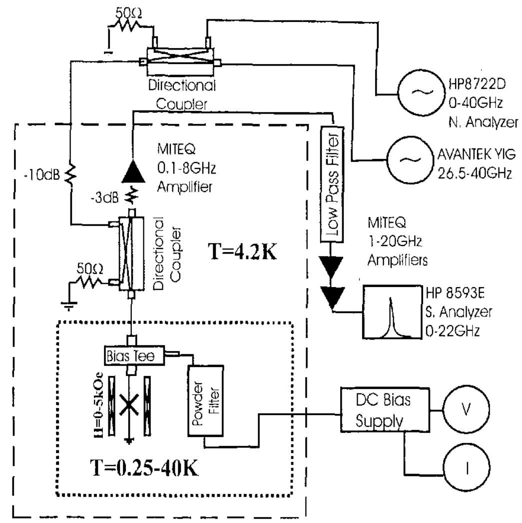

Fig. 1. Measurement Setup

II. DEVICES AND MEASUREMENT SETUP

The devices consist of a thin, narrow Al microbridge with dimensions d=13-17nm, W=0.1μm, and L=0.2-1μm, 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 [10]. The device parameters are summarized in Table I.

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 $T_{c,contact\ pads} \approx$ 0.6-1.0K. For $T_{bath} < T_{c,contact\ pads}$ 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 ^{3}He 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.

III. RESULTS

A. *I-V Curves and R vs. T*

I-V curves of device C in the absence of an external magnetic field are shown in Fig. 2. At temperatures ~ 0.6K and below, the small series resistance present is that of the cables and microstrip line used in a two point measurement of the resistance.

When the contact pads are in the normal state, a significant resistance (Figs. 3,4) exists even at temperatures well below T_c of the microbridge. For example, in device D, the transition temperature of the Al microbridge is ~2.4K and that of the contact pads is ~0.6K. At temperatures just below 2.4K where the superconducting energy gap is small, the observation of resistance can be explained due to charge imbalance effects. However, at 0.6K ($t=T/T_c$=0.25) and at small voltages, nearly all of the single electrons incident on the N-S boundary should be converted to Cooper pairs via Andreev reflection.

R vs. T curves were also measured without cold amplifiers, couplers, etc. attached to the device. This was done to verify that the observed resistance was not due to a suppression of superconductivity induced by coupled 4K radiation. Additionally, one batch of devices where normal metal contacts (no magnetic field applied) were also measured. The R vs T curves measured in these experiments were similar to Fig. 4.

Dividing this observed resistance by the normal state resistance and multiplying by the length of the microbridge

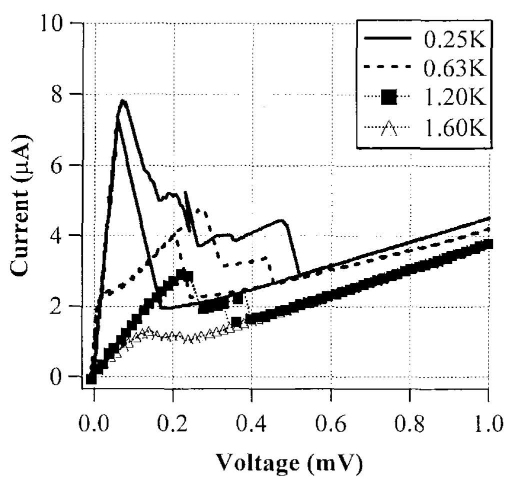

Fig. 2. I-V Curves for device C for bath temperature 0.25-1.6K. H=0.

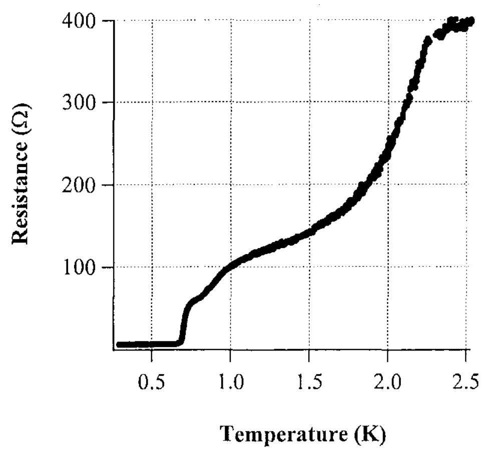

Fig 3. R vs. T of device D, H=0. The IV curves of this device are similar to those of device C, Fig. 2.

gives us the effective length of the resistive area in the microbridge. Comparing this length to the superconducting coherence length, determined by upper critical field measurements, we see that the length of the resistive region is ~ 6 coherence lengths. In structures shorter than this length (e.g. L=0.2μm) we did not observe a superconducting transition in the bridge when the contacts were in the normal state. This minimum length sets a limit on the IF bandwidth, via Eq. (2). For practical devices, the IF bandwidth can still be $\gtrsim$ 10GHz.

The cause of this series resistance must be proximity effect from the thick normal contacts; but there is no available theory for this geometry. A calculation of the position dependant energy gap using the Usadel formalism [11] applied to this geometry would be useful in understanding the origin of this resistance. Nevertheless, good conversion efficiency and low output noise are observed in these devices. For example. though approximately half of device A is proximitized normal, good sensitivity is seen at the optimum bias point where the resistance is close to the normal state resistance.

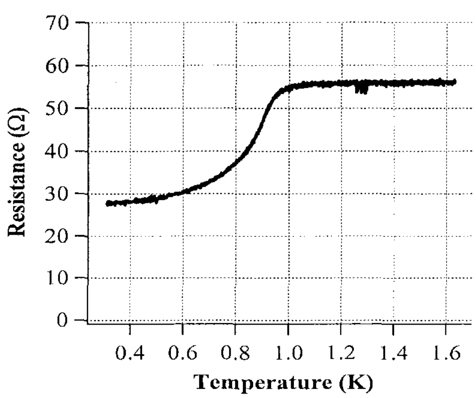

Fig. 4. R vs. T of device A. H=1.2kOe.

B. IF Bandwidth

The IF bandwidth depends on the bias point used. Measurements reported here are for bias points in the "resistive state" (>0.4mV in Fig. 2, 1.2K) where conventional HEB mixing models can be applied. The measured IF bandwidths ranged from 1.2-6 GHz. In Fig. 5 a comparison is made between the measured IF bandwidth and the value predicted from a calculation of the diffusion time. The bias points considered here 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.

C. Optimum LO Power

The LO power used in the mixing experiments is in the range of $\leqslant$ 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. 6. The mixer noise temperature is calculated from the output noise of the device and the conversion efficiency: $T_M(DSB)=T_{output}/2\eta$. 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).

D. Mixer Noise

In Fig. 7 the dependence of mixer noise and conversion efficiency on bias voltage is shown for device A. The minimum of the mixer noise temperature is ~4 K for device A. 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 some excess noise which was visible above f_{-3dB}, the origin of which was not explained [12]. For the Al HEBs, the total output noise is consistent with thermal fluctuation and Johnson noise contributions with

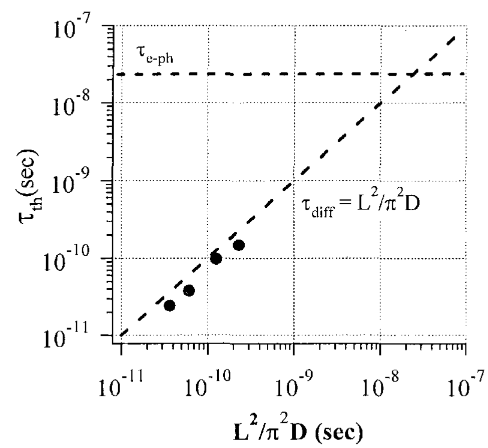

Fig. 5. IF Bandwidth: Measured & Predicted. The electron-phonon inelastic time is calculated for T=1.6K. The vertical axis is the measured relaxation time, where τ_{th} is determined experimentally using $\tau_{eff}=(2\pi f_{-3dB})^{-1}$.

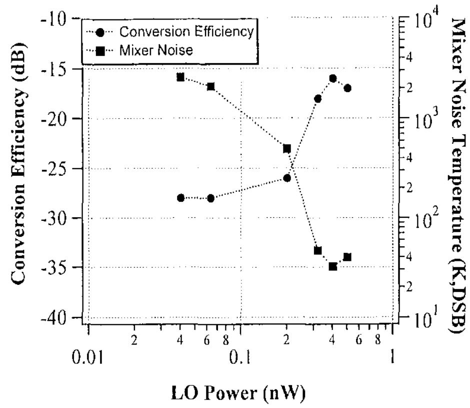

Fig. 6. Conversion Efficiency & Mixer Noise Temperature vs. LO Power. Device D. T=0.25K.

Johnson noise of the magnitude expected for $T \sim T_c$.

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 is ~ nW in these experiements, and also in those described in [13] at 618 GHz. The conversion efficiency at 618GHz, however, appears to be 10-15dB lower than the values quoted here. The origin of this discrepancy is currently being investigated. The measured output noise and conversion efficiency 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 [14]. 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 only tens of microvolts, output saturation due to background noise or a large input signal might be an issue. For example, if the sky backround at 1 THz is 100K, the voltage at the IF from downconverted radiation will be ~ 12 μV, assuming an IF bandwidth of 10 GHz and a conversion efficiency of −10dB. Al HEB based receivers would probably be most useful for space applications using cooled telescopes where the background radiation is significantly reduced.

For ground based applications where background radiation levels are higher, new devices based on Ta (T_c ~ 3-4K) are currently being investigated. These devices are predicted to have a two fold improvement in sensitivity compared to Nb HEBs, yet require four times less LO power. Since the materials properties of Ta and Nb are very similar, the Ta devices are expected to be similar in operation to previously tested Nb HEBs.

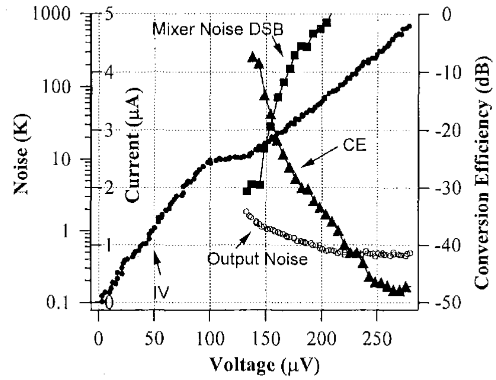

Fig. 7. Conversion Efficiency, Output Noise, and Mixer Noise vs. Bias Voltage for Device A. T=0.25K. H=1.2kOe.

References

[1] B.S. Karasik and W.R. McGrath, "Optimal choice of material for HEB superconducting mixers," *Proc. 9th Int. Symp. Space Terahertz Tech.*, pp. 73-78, Pasadena, California, 1998; D.E. Prober (unpublished).

[2] P.J. Burke et al., "Mixing and noise in diffusion and phonon cooled superconducting hot-electron bolometers," *J. Appl. Phys.*, vol. 85, pp. 1644-1653, 1 February 1999.

[3] R. A. Wyss, B.S. Karasik, W.R. McGrath, B. Bumble, H. LeDuc, "Noise and bandwidth measurements of diffusion-cooled Nb hot-electron bolometer mixers at frequencies above the energy gap," *Proc. 10th Int. Symp. Space Terahertz Tech,*, pp. 215-228, University of Virginia, Charlottesville, Virginia, 1999; B.S. Karasik, M.C. Gaidis, W.R. McGrath, B. Bumble, H.G. LeDuc, "Low noise in a diffusion-cooled hot-electron mixer at 2.5THz," *Appl. Phys. Lett.*, vol 71, pp. 1567-1569, 15 September 1997.

[4] E. Gerecht et al., "Improved Characteristics of NbN HEB mixers integrated with log-periodic antennas,"*Proc. 10th Int. Symp. Space Terahertz Tech.*, pp. 200-207, University of Virginia, Charlottesville, Virginia, 1999

[5] D.E. Prober, "Superconducting terahertz mixer using a transition-edge microbolometer,"*Appl.Phys.Lett.*,vol.62,pp.2119-2121, 26 April 1993.

[6] P.J. Burke, Ph.D. thesis, Yale University, 1997.

[7] J. Schubert et al., "Noise temperature and sensitivity of a NbN hot-electron mixer at frequencies from 0.7-5.2 Thz," *Proc. 10th Int. Symp. Space Terahertz Tech.*, pp. 190-199, University of Virginia, Charlottesville, Virginia, 1999.

[8] B.S. Karasik and A.I. Elantiev, "Noise temperature limit of a superconducting hot-electron bolometer mixer," *Appl. Phys. Lett.*, vol 68, pp. 853-855, 5 February 1996.

[9] C.M. Caves, "Quantum limits on noise in linear amplifiers," *Phys. Rev. D*, vol 26, pp. 1817-1839, 15 October 1982.

[10] P.M. Echternach, H.G. LeDuc, A. Skalare, W.R. McGrath, "Fabrication of an aluminum based hot-electron mixer for terahertz applications," *Proc. 10th Int. Symp. Space Terahertz Tech.*, pp. 261-268, University of Virginia, Charlottesville, Virginia, 1999.

[11] S. Gueron, Ph.D. thesis, CEA Saclay, 1997.

[12] P.J. Burke et al., "Spectrum of thermal fluctuation noise in diffusion and phonon cooled hot-electron mixers," *Appl. Phys. Lett.*, vol. 72, pp. 1516-1518, 23 March 1998.

[13] A.Skalare et al., "Diffusion-cooled aluminum hot-electron bolometer mixers at submillimeter wavelengths," *Proc. 11th Int. Symp. Space Terahertz Tech*, submitted for publication; A. Skalare et al, "Aluminum hot-electron bolometer mixers at submillimeter wavelengths," *IEEE Trans. Appl. Supercond (ASC 00)*, submitted for publication.

[14] S.Matsuura et al., "A traveling-wave THz photomixer based on angle-tuned phase matching," *Appl. Phys. Lett.*, vol 74, pp. 2872-2874, 10 May 1999.