Aluminum Hot-Electron Bolometer Mixers at Submillimeter Wavelengths

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Abstract—**Diffusion-cooled aluminum hot-electron bolometer (HEB) mixers are of interest for low-noise high resolution THz-frequency spectroscopy within astrophysics. Al HEB mixers offer operation with an order of magnitude less local oscillator power, higher intermediate frequency bandwidth and potentially lower noise than competing devices made from other materials. We report on mixer experiments at 618 GHz with devices fabricated from films with sheet resistances in the range from about 55 Ω down to about 9 Ω per square. Intermediate frequency bandwidths of up to 3 GHz were measured (1 μm long device), with absorbed local oscillator power levels of 0.5 to 6 nW and mixer conversion up to -21.5 dB. High input coupling efficiency implies that the electrons in the device are able to thermalize before escaping from the device. It was found that the long coherence length complicates mixer operations due to the proximity of the contact pads. Also, saturation at the IF frequency may be a concern for this type of device, and warrants further studies.**

Index Terms—**Bolometer, mixer, superconductor, submillimeter, aluminum**

I. Introduction

Superconducting hot-electron bolometer (HEB) mixers [1,2] have emerged as the most promising technology at frequencies above about 1 THz for extremely low-noise molecular spectroscopy applications in astrophysics. A primary reason is that HEB mixers are not limited by the upper frequency limit that the superconducting energy gap imposes on competing SIS mixers (about 700 GHz for Nb, about 1200 GHz for NbTiN). In fact, the RF power dissipation in the HEB device is more uniform above the gap frequency, and operation up to tens of THz should be possible. In addition to low-noise operation, superconducting HEB mixers provide intermediate frequency (IF) bandwidths that are much higher than conventional semiconductor bolometers (several GHz), and local oscillator (LO) power requirements in the nW range (rather than μW's for competing mixers). HEB mixers are planned to be used for the spaceborne ESA/NASA FIRST mission, for NASA's airborne SOFIA observatory, and for a Long-Duration Balloon Instrument. These particular instruments will operate at frequencies ranging from about 1 THz up to 3 THz.

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Aluminum diffusion-cooled HEB mixers are predicted to have several significant advantages compared to existing diffusion-cooled Nb and phonon-cooled NbN devices, namely even less LO power, lower noise, and higher IF bandwidth [3]. The low LO power requirements are particularly important, since the solid-state frequency-multiplied sources that are being developed for use above 1 THz will likely be quite weak, and may not be able to drive other existing types of bolometers. The LO power should scale as T_C^2, where T_C is the transition temperature of the device film [3, 4]. This would result in only a few nW for Al as compared with the 20-80 nW that is required for Nb [5, 6]. Niobium devices with somewhat smaller LO power requirements can be fabricated from dirtier films, but this will result in suppressed IF bandwidths. In this paper, we report the first submillimeter wave measurements with a superconducting aluminum HEB mixer, and compare these to the theoretical predictions.

II. The HEB Device

The aluminum HEB devices were fabricated together with their mixer circuits using a PMMA shadow-mask technique [7]. All the necessary process steps take place without breaking vacuum, which is critical to avoid contamination and/or oxidization of the Al films. The device film thicknesses were 13 to 17 nm. The "normal" metal contacts at the ends of the microbridge were made of a sandwich structure consisting of 63 nm Al, 28 nm Ti and 28 nm Au, see Fig. 1, which prevents interdiffusion between the device and the contacts. All devices had a width of 0.1 μm, and lengths of 0.3, 0.6 and 1.0 μm. The RF circuit consists of twin-slot antennas, which were coupled to either a microstrip circuit or to a coplanar waveguide circuit. For most devices the transition temperatures ranged from about 1.6 to 1.8 K, with a suppressed transition temperature at the ends of the devices of about 0.6 to 1.0 K. Fig.2 shows the resistance versus temperature (R vs. T) curve for a 1 μm long HEB (device #1 in Table I). The end effect appears to extend 200

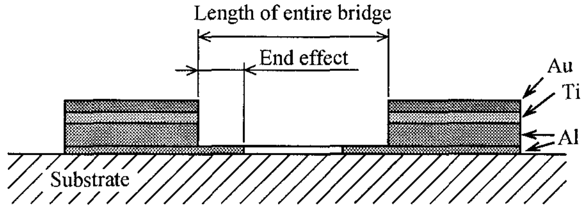

Fig. 1. Schematic side view of a device. The end effects extend into the bridge between 100 nm for high-resistivity films and 300 nm for the cleanest 9 Ω /square films.

to 300 nm into the device, so that for the cleanest device films (9 ohm/square) even a 0.6 μm device exhibits a single transition at about 1.3 K.

III. Experimental Set-Up

The experiments were made at about 400 mK using a helium-3 cryostat. The device chips were attached to the back plane of an elliptic silicon lens, and connected to a DC/IF microstrip circuit with several aluminum bond wires. In the different measurements either a 1.4 GHz cooled HEMT amplifier that was heat sunk to 4 K, or a 0.5 to 18 GHz FET amplifier that was heatsunk to 77 K was used. Stainless steel coaxial cables, a black polyethylene/diamond dust infrared filter at 4 K, and a polyethylene/Zitex filter at 77 K were used to reduce the heat load on the mixer assembly and HEB device. A frequency-multiplied Gunn at 618 GHz and a tunable backward-wave oscillator (BWO) were used as test signal and as LO in the mixer measurements.

IV. RF Measurements

A. Input Coupling Efficiency and Local Oscillator Power

An important issue for aluminum HEB's is the long electron-electron inelastic time at the Fermi level, which could result in incomplete thermalization of the "hot" electrons. The RF input coupling efficiency is one way to study this issue, since poor coupling could indicate that electrons that are heated by the absorption of an RF photon escape from the device before fully sharing their energy with the rest of the electrons. The coupling efficiency was estimated by adjusting the DC bias

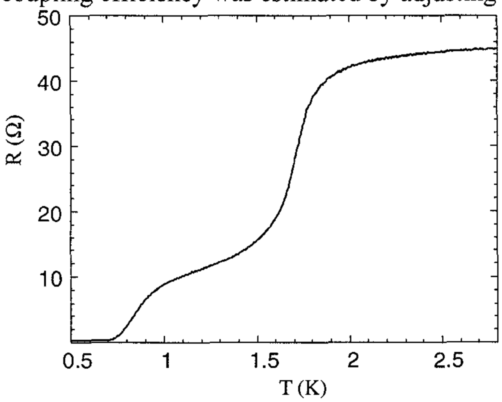

Fig.2. Resistance vs. temperature curve for a 1 μm long device.

TABLE I
Results of Aluminum Mixer Measurements at 618 GHz

Device	L (μm)	R (Ω)	Conversion (dB SSB)	BW (GHz)	LO Power (nW)
#1	1.0	448	-21 to −33	1 to 2.7	0.5
#2	1.0	285	-21	3	1.3
#3	0.6	255	-20	3	3.7
#4	0.6	330	—	1.7	0.9
#5	0.6	100	-29	3	2.7
#6	0.6	106	-21.5	—	5.7

The conversion efficiency does not include losses in the input optics.

to maintain a constant device resistance while switching the input beam between one Eccosorb™ blackbody radiator at 295 K and another one at 77 K. The difference in DC heating that is required to maintain a constant resistance is a coarse measure of the difference in absorbed radiation from the two loads. With the RF bandwidth of the mixer circuit and the load temperatures known, the coupling efficiency was estimated to about −4.7 dB for a 106 Ω device [8]. This value is consistent with those of Nb bolometers in the same type of circuit, between −5 and −8 dB [6, 9].

The amount of absorbed LO power was estimated by the effect on the DC properties, giving values between 0.5 nW and 6 nW. This is about 20 times less than for Nb, which is expected since the LO power should scale as T_c^2. How much power is actually incident on the device is not known, however, since the coupling between the beam pattern of the LO source and the antenna pattern of the mixer is unknown. An upper limit for the LO power incident on the mixer can be found by noting that a frequency multiplier that produced less then than 100 μW could drive device #6 in Table I completely normal. With the known losses in the beamsplitter (7 dB) and the losses in filters combined with the spreading of the unfocussed beam from the multiplier (20 dB), the incident LO power is < 200 nW. This shows that predictions that incident power levels on the order of μW's would required are not applicable to these devices [10].

B. Conversion Efficiency and IF Bandwidth

The mixer conversion efficiency (η) has been measured as a function of intermediate frequency, see Table I. The conversion efficiency was defined as the ratio of the output IF power to the RF power absorbed in the device from a monochromatic source, so that losses in the input optics and in the passive circuit elements were not included. The conversion efficiencies were typically −21 to −20 dB single sideband (SSB), with 3 dB bandwidths up to 3 GHz. Except for device #5, all the measurements in Table I were optimized for highest conversion efficiency.

Figures 3 and 4 show the dependence of η with bias voltage for device #1 in Table I. The bandwidth is at its lowest and η is at its highest at *V1* where the IV curve shows strong self-heating, consistent with our experience of Nb HEB mixers. At *V1*, η ≈ −21 dB and the bandwidth is 1 GHz. This clearly shows the effect of the high electron diffusivity of these aluminum films, as this IF bandwidth is several times higher than that obtained for niobium devices of the same length. Device #3 is 0.6 μm long, but gave a bandwidth of about 3 GHz with a similar conversion efficiency. This is consistent with the L^{-2} dependence of the bandwidth that is expected from a diffusion-cooled HEB, with L being the device length.

The DC properties of the 1 μm Al bolometers appear qualitatively similar to those measured for Nb devices. This is not the case for the shorter 0.6 μm long devices where the end effect appears proportionately more significant. This can be seen in Fig. 5, where the device exhibits a significant DC resistance at low bias voltages, that is associated with the two end regions illustrated in Fig.1. The "step" in the IV curve in Fig.5 is associated with the transition at the center of the bridge, and this is the bias regime that normally gives the highest conversion efficiency. The maximum output power in Fig. 5 corresponds to a conversion efficiency of –21.5 dB SSB. The total IF noise level referred to the input of the IF system was equivalent to about 15 K, with about 10 K due to the amplifiers. With an input coupling efficiency of –4.7 dB this leads to an approximate receiver noise of 3100 K DSB, with the contribution from the mixer itself being about 1000 K DSB (these noise temperatures are referred to a reference plane immediately outside of the cryostat window).

V. Discussion

A. Device End Effects

The end effects that are observed in both IV curves and R vs. T curves are believed to be a combination of proximity effects and charge imbalance [11]. One indication of the proximity effect is that two transitions are seen in the R vs. T curves, see Fig.2. The lower of the two transistions, at about 0.85 K in Fig.2, occurs in the proximitized regions. This transition temperature, when caused by proximity, should generally fall somewhere between that of the contact pads (0.6 K) and that of the central part of the bridge. A similar lower step could be expected from charge imbalance, but its origin would be different. In the charge imbalance model the lower step in the curve would occur right at the (0.6 K) transition of the contact pads, above which the device ends form the S–N interfaces that are required for charge imbalance to occur, and below which the device ends would instead form S–S interfaces. In our measurements this end-region transition actually varies from just over 0.6 K up to as high as 1.3 K, depending on the device film properties, which would indicate that the most significant mechanism is proximity rather than charge imbalance. However, charge imbalance still affects the detailed shape of the measured R vs. T curves.

When the device is operated as a mixer, the mechanisms described above can cause the "series resistance" that is seen at low voltage in the LO-pumped IV curve in Fig.5. Unfortunately, this resistance has several potential adverse effects on the operation of the mixer. Since it is in series with the IF system it will dissipate some of the IF output power

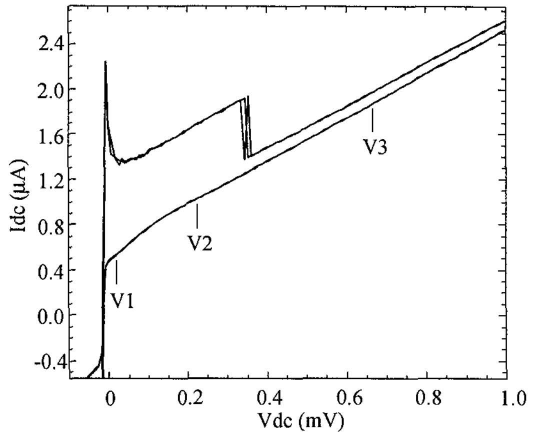

Fig. 3. Unpumped and local oscillator pumped IV curves for the 1 μm long device #1 from Table 1. The marked bias voltages were used in the bandwidth measurements in Fig.4.

from the mixing process, which lowers the conversion efficiency. It also changes the electrical load line that is seen by the central (actively mixing) part of the device, which can cause bias oscillations. These may be hard to identify in Y-factor (noise) measurements. However, when they occur they are easily observed as sidebands to the IF output signal when using a monochromatic signal source. The perhaps most significant effect on the mixer is that the end effects prevent the use of very short and fast devices, which would be completely proximitized with too low transition temperatures for efficient mixing. If the device length is 300 nm, the maximum IF bandwidth is $\Delta f = \pi D/(2L^2)$ = 17 GHz (with $D=10 cm^2/s$), which is considerably lower than the 157 GHz that is calculated for a 100 nm device. One way to eliminate the complications may be to fabricate devices with geometrically modified ends. A wider device end-region might still be proximitized, but it would have a lower resistance and therefore impair the mixing process less, and it would also heat sink the central parts of the bridge better, which may also give a faster device.

B. Saturation; Use of a Magnetic Field

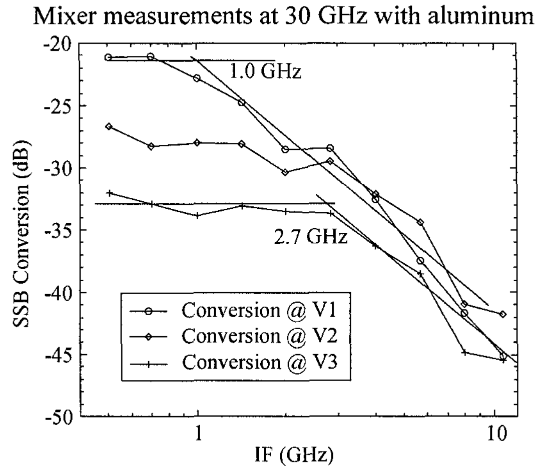

Fig. 4. Conversion efficiency vs. intermediate frequency at the three bias points marked in Fig.3. The signal was kept at a constant frequency of 618 GHz as the local oscillator frequency was changed.

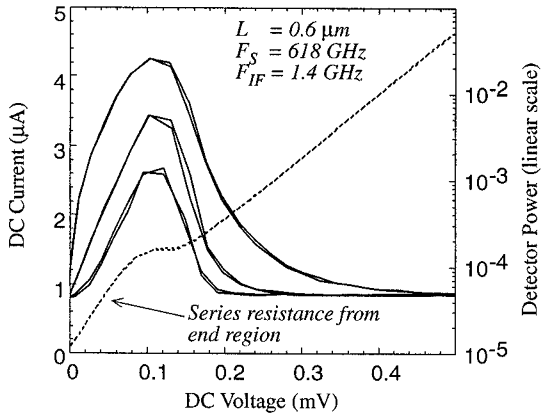

Fig.5. If output signal vs. bias voltage at three different signal power levels for device #6. The LO-pumped IV curve is also shown.

devices have been reported in [12, 13], using a magnetic field to suppress the superconductivity of the contact pads. These measurements gave considerably higher conversion efficiency (-8 dB) over a very narrow voltage interval in the DC IV curve. Although the discrepancy between the 30 GHz and 618 GHz measurements is not conclusively understood at this point, one likely cause is IF output saturation from downconverted thermal radiation in the 618 GHz experiment. In order to study this, thin sheets of cold microwave absorber have been placed in the optical path of the mixer in order to suppress the incident thermal radiation. In order to emulate at 618 GHz the other conditions in the 30 GHz experiments, an electromagnet has also been installed in the cryostat. Measurements in this configuration are already underway, and will be reported in future publications.

SUMMARY

We have measured absorbed LO power, conversion efficiency IF bandwidth of aluminum HEB mixers at around 618 GHz. As expected from theory, the LO power was about 20 times lower than for similar devices made from niobium. However, the highest measured conversion efficiency was only about –21 dB single-sideband (SSB), which is considerably lower than measurements with Nb bolometers as well as lower than measurements at 30 GHz with aluminum [12, 13]. IF bandwidths of up to 3 GHz were measured. A receiver noise temperature of about 3100 K double sideband (DSB), of which about 2000 K is IF amplifier noise, can be inferred from measurements of input coupling efficiency, conversion efficiency, and mixer output noise. It should be cautioned, however, that since these numbers were not achieved through a calibrated Y-factor measurement the errors could potentially large.

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