Characterization of NbTiN Hot Electron Bolometer Mixers at 0.8 THz

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Abstract

We present recent measurements of receiver noise temperature and intermediate frequency bandwidth performed at a local oscillator frequency of 0.8 THz for waveguide NbTiN Hot Electron Bolometer mixers of various dimensions. These devices are fabricated from an NbTiN film deposited on crystalline quartz substrates with an intermediate AlN buffer layer. The lengths of the mixer elements vary from 0.3 to 0.5 μm and their widths vary from 3 to 10 μm. Critical temperatures are typically 8.5 K, and critical current densities are about 13 mA/μm^2. A double side band receiver noise temperature as low as 550 K has been measured at an IF frequency of 1.8 GHz, with a conversion loss of around 14 dB. At the optimum bias point for low noise operation, these mixers have an instantaneous bandwidth of only 1.1 GHz. This may be increased by either overpumping the mixer or increasing the bias voltage. However, such conditions result in increased mixer conversion loss and poorer overall performance.

Introduction

At the present time, there are only two ground-based telescopes equipped with heterodyne receivers designed to operate at frequencies in excess of 1 THz, one in Northern Chile [1] and another at the South Pole [2]. In both cases, NbN thin film phonon-cooled Hot Electron Bolometer (HEB) mixers are employed as the mixing element as they have been proven to offer low noise performance. Furthermore, mixers of this type are currently being developed for receivers to be used in future air- and space- borne missions, such as Hershel and SOFIA, for which the deployment of similar receivers is envisioned [3, 4].

Mixers incorporating thin film NbTiN HEBs have previously demonstrated low-noise performance [5] and could be a good alternative to the NbN devices currently in use for low-noise heterodyne applications. In this paper, we report on the performance of waveguide HEB mixers at between 0.75 and 1.05 THz fabricated from superconducting NbTiN thin film deposited on an AlN buffer layer over crystalline quartz. This study is a continuation of work previously made at lower frequencies 0.6-0.8 THz [5].

Device preparation

The mixers used in this study were all fabricated from a 4 nm thick superconducting NbTiN film. This film was deposited over a 20 nm AlN buffer layer on a Z-cut crystalline quartz substrate by reactive DC sputtering. The buffer layer is used to improve the quality of superconducting film and to provide a better phonon match to the supporting substrate. Crystalline quartz was chosen as the substrate material due to its relatively small dielectric constant and reasonably good thermal properties. The details of device processing are described in [5]. After fabrication, the wafer is lapped to a thickness of 30 μm before dicing into chips, 2 mm long and 0.12 mm wide.

In this investigation, we have made a series of DC and heterodyne measurements using a number of different sized NbTiN micro-bridges with dimensions outlined in Table 1. In essence, the lengths of the mixer elements vary from 0.3 to 0.5 μm and their widths vary from 3 to 10 μm, which results in a device volume variation of a factor of 5.5.

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DC characteristics

In Figure 1 we plot the resistance versus temperature curve of a representative NbTiN mixer. The critical temperature is estimated at 8.5 K, and the transition width is about 1 K. This mixer has a critical current of 150 μA at a bath temperature of 4.2 K, which translates to a critical current density of 12.5 mA/μm^2. This is close to the average of 12.7 mA/μm^2 for all of the measured devices from the same wafer.

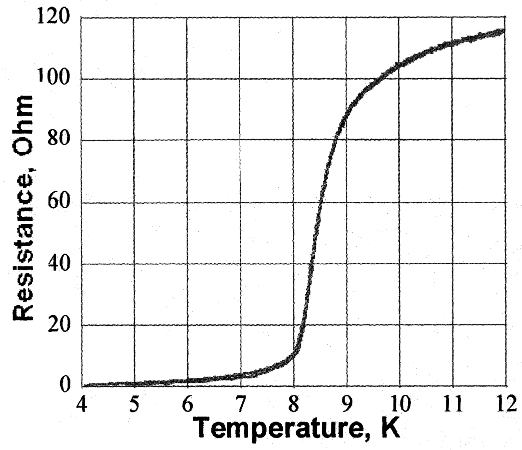

Figure 1: Resistance – Temperature curve of an NbTiN device, 0.3 μm long by 3 μm wide.

In Figure 2 we plot the normal state resistance versus the bridge size, length divided by width, for the set of devices studied. From the figure we obtain a sheet resistance of 1000 Ohms/square. Furthermore, the data is well-fit by a straight line which demonstrates the fact that the NbTiN film is highly uniform.

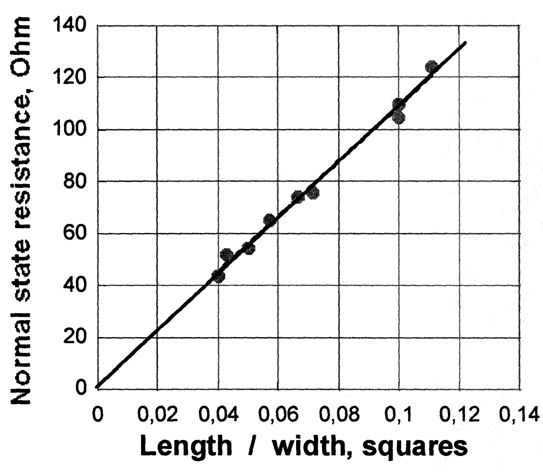

Figure 2: The normal state resistance vs. bolometer size.

Receiver noise measurements

Double side band (DSB) noise temperature measurements have been performed using the standard Y-factor technique with the mixer, a fixed-tuned waveguide structure, mounted in a liquid helium filled cryostat. A Martin-Puplett interferometer was used to combine signal and local oscillator. The signal passes through a vacuum window, made from 0.5 mm Teflon sheet, and two Zitex G-108 infrared blocking filters, mounted on the 77 K shield and on the 4.2 K cold plate, before entering the mixer. This measurement set up is discussed in more detail in [6]. Output from the mixer passes to a low noise intermediate frequency (IF) amplifier, and 1 GHz wide filters are used to select either a 1.8 or 3 GHz center frequency.

Current - Voltage characteristics and IF output power in response to hot and cold loads are presented in Figure 3 for mixer b54n4 (size 0.3 x 7 μm^2). At an IF of 1.8 GHz, the best measured Y-factor is 1.3, which corresponds to a receiver noise of 650 K, and the conversion loss is estimated at 14 dB.

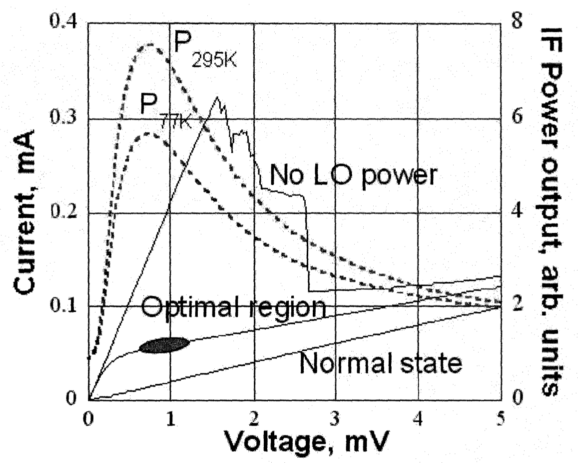

Figure 3: Current – Voltage (I-V) characteristics of an NbTiN HEB mixer b54n4 (see Table 1) with and without LO power at 800 GHz, and in the normal state. The I-V curves were measured using a 2-point measurement set-up in which the series resistance is a few ohms. The shaded region shows optimal bias region for low noise. The dotted lines represent the IF output power as a function of bias voltage in response to hot and cold loads.

Device	Length, µm	Width, µm	Resistance at 295 K, Ohm	Critical Current at 4.2 K, mA	DSB Noise Temperature, (K)*	3 dB roll-off freq., GHz
b54n2	0.3	3	99	0.15	620	1.2
b54n3	0.3	4.5	75	0.23	690	0.9
b54n4	0.3	7	52	0.32	570	0.9
b54n8	0.4	4	88	0.21	790	1
b54n9	0.4	7	62	0.43	680	1.2
b54n10	0.4	10	45	0.53	550	1.2
b54n13	0.5	4.5	110	0.21	700	1.4
b54n14	0.5	7	78	0.31	590	1.3
b53n15	0.5	10	50	0.51	690	1

*Measured at the IF central frequency 1.8 GHz and the bandwidth 1 GHz.

Table 1 DC characteristics and RF performance, measured at LO frequency of 0.8 THz, for the different NbTiN HEB mixers. In all cases, thickness of NbTiN superconducting film is 4 nm.

Also in Table 1 we list the measured DSB receiver noise temperature for all nine devices at an LO frequency of 0.8 THz and an IF center frequency 1.8 GHz. Clearly, the noise performance of these mixers has only weak dependence on the bolometer dimensions. This is not surprising since the bolometer resistance only varies by a factor of two for the devices tested so far. It would be instructive to extend the range of mixer dimensions to include a larger resistance variation.

We have also measured DSB receiver noise temperature across the frequency range: 0.75 to 1.05 THz, and in Figure 4 we plot the noise performance for the 3 GHz IF. Also shown for comparison is the measured noise performance for the 1.8 GHz IF at an LO frequency 0.8 THz. The higher noise temperature at 3 GHz IF is due to the small IF gain bandwidth of these NbTiN mixers (see below). However, the increase in noise temperature (~20 %) is relatively small. From the figure we note that the noise temperature is below 1000 K up to 0.87 THz even with the 3 GHz IF.

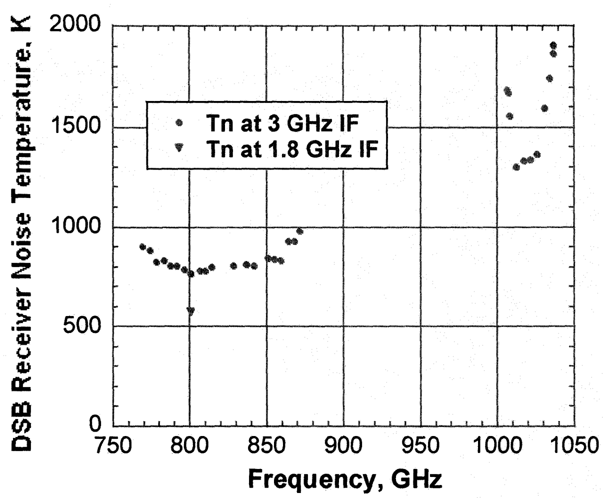

Figure 4: The Double side band receiver noise temperature measured around 0.8 THz and 1.026 THz for the NbTiN mixer with microbridge dimensions 0.3 x 7 μm^2. The circles represent measurements at an IF centered on 3 GHz, and the triangle is for the 1.8 GHz IF. In both cases, the measured bandwidth is 1 GHz.

Bandwidth at high bias

We have also measured the IF gain dependence at the optimal bias point for each of the mixers using a thermal noise source: a ceramic infrared radiating element focused by an off-axis parabolic mirror. This technique has been described previously in [7]. In each case, the experimental data has been fitted to the curve $1/(1+(f/f_{3dB})^2)$, where f_{3dB} is the characteristic 3 dB roll-off frequency. Referring to Table 1, all of the measured devices demonstrate a 3 dB roll-off frequency of about 1.1 GHz at optimal bias point. Since there appears to be no dependence on device length, we conclude that the cooling mechanism for these NbTiN mixers is predominantly via phonons rather than diffusion.

We have also measured the mixer gain dependence at high bias, and in Figure 5 we plot the measured IF output signal as a function of IF at three bias voltages under optimum LO drive. The curves have not been shifted relative to one another. Rather, there is a significant loss in conversion at higher bias voltages, even though the 3 dB roll-off frequency increases from 1 GHz at 1.1 mV bias to 3.7 GHz at 7 mV bias.

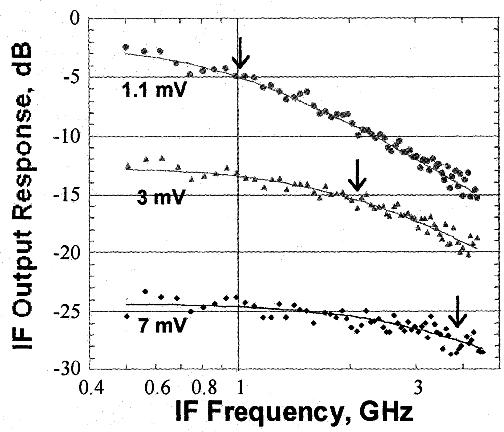

Figure 5: IF gain bandwidth measurements for mixer b54n4 at three bias voltages: 1.1, 3 and 7 mV. The experimental data points are shown and the solid lines give the best fit single pole roll-off of $1/(1+(f/f_{3dB})^2)$ to each data set. The arrows show the fitted 3 dB roll-off frequencies (f_{3dB}).

Conclusion

We have investigated the performance of NbTiN HEB waveguide mixers deposited on AlN buffer layer over quartz have at 0.8 THz. These devices demonstrated good uniformity DC characteristics. A double side band receiver noise temperature of 550 K has been measured at 0.8 THz for a 1 GHz-wide IF centered at 1.8 GHz. Finally, the measured 3-dB IF roll-off frequency is about 1.1 GHz at the optimal bias point, and operation at higher bias a yields higher roll-off frequency but at the expense of increased conversion loss.

Acknowledgment

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