A Low-noise NbTiN Hot Electron Bolometer Mixer

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Abstract

Hot electron bolometer (HEB) mixer elements, based on Niobium Titanium Nitride (NbTiN) thin film technology, have been fabricated on crystalline quartz substrates over a 20 nm thick AlN buffer layer. The film was patterned by optical lithography, yielding bolometer elements that measure about 1 μm long and between 2 and 12 μm wide. These mixer chips were mounted in a fixed-tuned waveguide mixer block, and tested in the 600 and 800 GHz frequency range. The 3-dB output bandwidth of these mixers was determined to be about 2.5 GHz and we measured a receiver noise temperature of 270 K at 630 GHz using an intermediate frequency of 1.5 GHz. The receiver has excellent amplitude stability and the noise temperature measurements are highly repeatable. An 800 GHz receiver incorporating one of these mixer chips has recently been installed at the Sub-Millimeter Telescope in Arizona for field test and for astronomical observations.

I. Introduction

In recent years, heterodyne receivers based on the superconductive Hot Electron Bolometer (HEB) mixer have begun to emerge as the instrument of choice for ultra-sensitive spectroscopic applications at THz frequencies. Two types of HEB mixers have been developed: the phonon-cooled mixer [1] and the diffusion cooled mixer [2]. In a phonon-cooled HEB mixer, hot electrons produced by THz photons are cooled through interaction with the lattice. Phonons are responsible for transferring the excess energy to the substrate on which the film is deposited. Until now, NbN has been the material of choice for this type of mixer [3]. Diffusion cooled HEB mixers, on the other hand, depend on the out diffusion of the hot electrons in extremely short niobium or aluminium thin film bridges to large metal electrodes [4].

Niobium Titanium Nitride (NbTiN) has largely been developed [5] for Superconductor-Insulator-Superconductor (SIS) mixers which now operate beyond 1 THz. NbTiN is a solid solution of NbN and TiN (both B1 phase superconductiors), and it has properties that resemble NbN, and it is reasonable to assume that NbTiN thin films can also be used in phonon-cooled HEB mixers. In this paper, we report on the first successful demonstration of NbTiN thin film technology to low-noise HEB receivers. We present both laboratory and field data in the frequency range 600 – 800 GHz.

II. Fabrication Process

We chose Z-cut crystalline quartz as the substrate material because our NbTiN HEB mixers are designed to work in a waveguide mount. In order to improve the quality of the NbTiN film, we have added an Aluminium Nitride (AlN) buffer layer. Details of the fabrication process can be summarized as follows:

a) A 20 nm thick AlN layer is first deposited onto the crystalline quartz substrate using RF sputtering of Al in an atmosphere of Ar and N_2. The deposition rate is 10 nm/min.
b) The quartz substrate is then heated to a temperature of 375^o C.
c) The NbTiN thin film is deposited by DC sputtering of NbTi alloy target in an atmosphere of Ar and N_2. The substrate is also RF biased during this operation. Following a short period of pre-sputtering, the substrate is moved into the normal sputtering position for 6 seconds, after which the power is shut off. The deposition rate for thick NbTiN layers made under the same conditions is 40 nm/min.

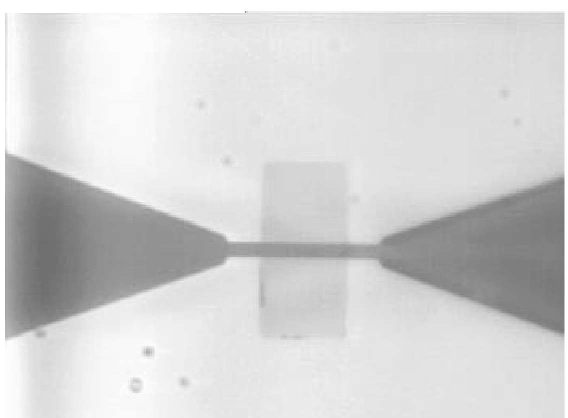

Fig. 1 Photograph of an NbTiN HEB device. The width of the element is 8 μm. The distance between the normal electrodes is about 1 μm. This photo is taken on an optical microscope looking from the back side of the quartz substrate.

d) The NbTiN thin film is next patterned by using Reactive Ion Etching.
e) The normal metal electrodes, which also form the IF filters, are deposited after a brief ion beam cleaning of the NbTiN surface. The electrodes consist of 5 nm of titanium and 30 nm of gold, and are patterned using a lift-off technique with optical lithography.

The length of our HEB devices is about 1 µm. In order to provide a range of impedances, we have fabricated HEB devices of variable width, from 2 to 12 µm. Fig. 1 shows a typical device which is 8 µm wide.

III. Device Characteristics

As a result of the short deposition time of the NbTiN thin film and the deposition process, the thickness of the film is not uniform over the whole wafer. We estimate that the thickness of the film is about 5 nm on average. The resistance ratio R_{20}/R_{300} is typically 1.14. The critical current density is about 1 MA/cm^{-2} and the sheet resistance of the finished device varies between 850 and 1150 Ω/•.

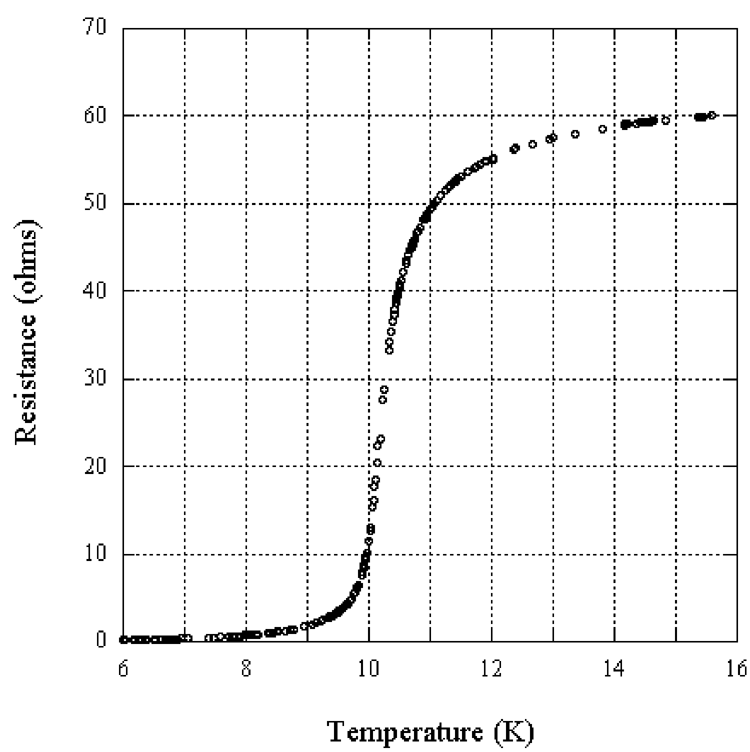

Fig. 2 Resistance – Temperature curve of a typical NbTiN HEB device around the critical temperature.

The Resistance – Temperature curve of a typical device is plotted in Fig. 2. It can be seen that the critical temperature of the device is about 10 K and that the R-T curve has a long tail on the high temperature side. The reason for this non-ideal behavior is not yet understood.

To determine the IF bandwidth of the NbTiN mixers, we have performed heterodyne mixing experiments with two phase-locked 600 GHz sources, one used as a signal source and one as an LO source. The signal power and frequency were kept constant as the IF was varied between 0.5 and 7 GHz by tuning the LO source and regulating the LO power to maintain a fixed operating point. The results are summarized in Fig. 3, where it can be seen that the 3-dB IF bandwidth varies with the applied bias voltage. For a bias of 1 mV, the measured bandwidth is 1.7 GHz. It rises to 1.9 GHz at 2 mV bias, and 2.5 GHz at a bias of 4 mV. These values are marginally better than the data from NbN HEB deposited directly on crystalline quartz [6].

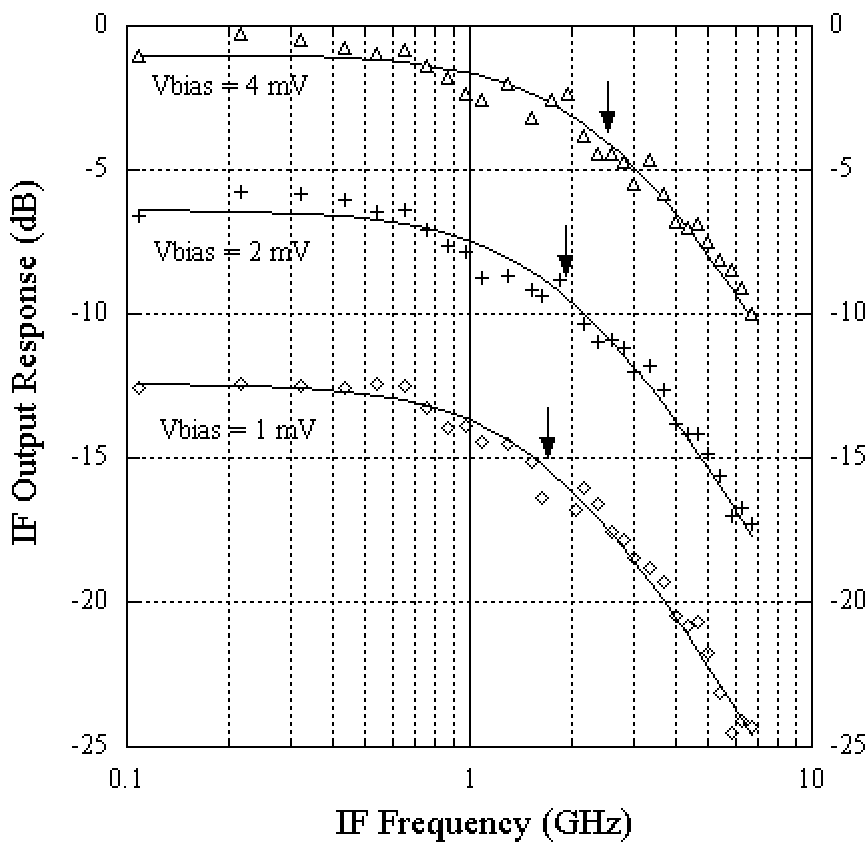

Fig. 3 IF Gain Bandwidth measurement of NbTiN HEB mixers operating at around 600 GHz. The solid curves are the best fit single pole roll-off response for each bias voltage setting. Note that the curves are shifted vertically relative to each other for display purposes only. The 3-dB rollover frequencies are marked by arrows. The error of the fit is about 0.2 GHz.

IV. Noise Measurement

NbTiN mixer chips were installed in our fixed-tuned waveguide mixer block for noise measurement using the standard Y-factor technique. This setup has been described previously [7]. The IF center frequency is 1.5 GHz and the bandwidth is 100 MHz. At 630 GHz, a 12 μm wide device gives a Y-factor of 1.65 at a bias voltage of 3 mV. Both the pumped and unpumped Current-Voltage characteristics, as well as the receiver output in response to the hot and cold loads, are recorded in Fig. 4. Note that the maximum receiver output power occurs at a bias voltage of 2.3 mV.

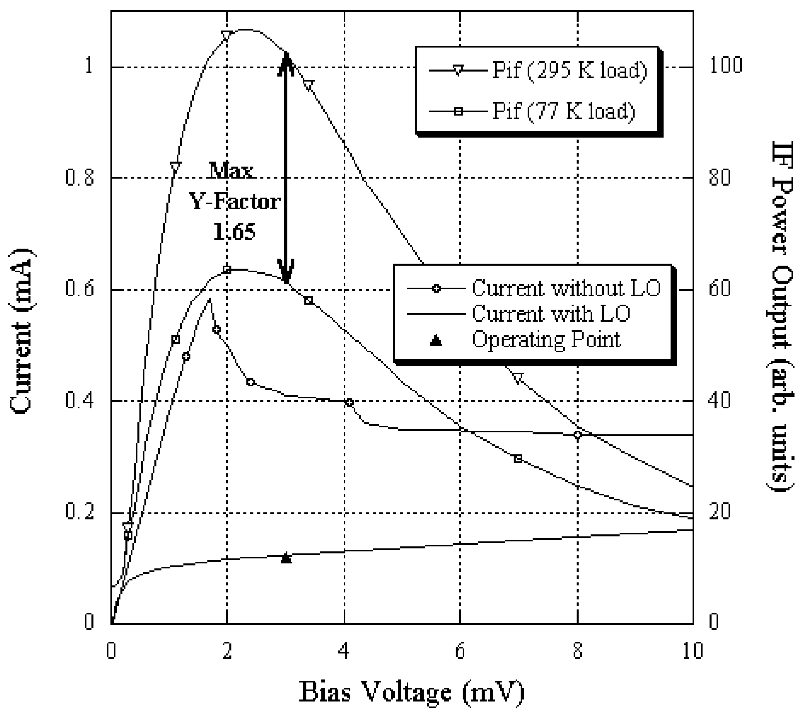

Fig. 4 Current-voltage characteristics of a 12 μm wide NbTiN HEB mixer, with and without LO drive at 630 GHz. Also shown is the receiver IF power as a function of bias voltage in response to hot (295K) and cold (77K) loads. A maximum Y-factor is recorded at a bias voltage of 3 mV and a bias current of 115 μA.

A number of 600 GHz chips have been tested. The results at 636 GHz are summarized in Table I. The measured data show that the performance improves as the resistance of the mixer is reduced. This is in line with our waveguide embedding impedance of about 40 ohms. Also, since the optimal bias point is about 3.5 mV, the achievable IF bandwidth should be close to 2.5 GHz.

Device Width (mm)	Normal State Resistance (W)	Critical Current (mA)	DSB Noise Temp. (K)	Estimated DSB Conversion Loss (dB)	Optimum Bias Point
5	170	255	525	-9	3.5 mV, 65 μA
8	110	330	445	-8	3.5 mV, 95 μA
12	95	500	375	-7	3.8 mV, 130 μA
12	80	600	270	-6	3 mV, 115 μA

Table I DC Characteristics and RF performance measured at 636 GHz of different NbTiN HEB mixer chips. Length of device is 1 μm.

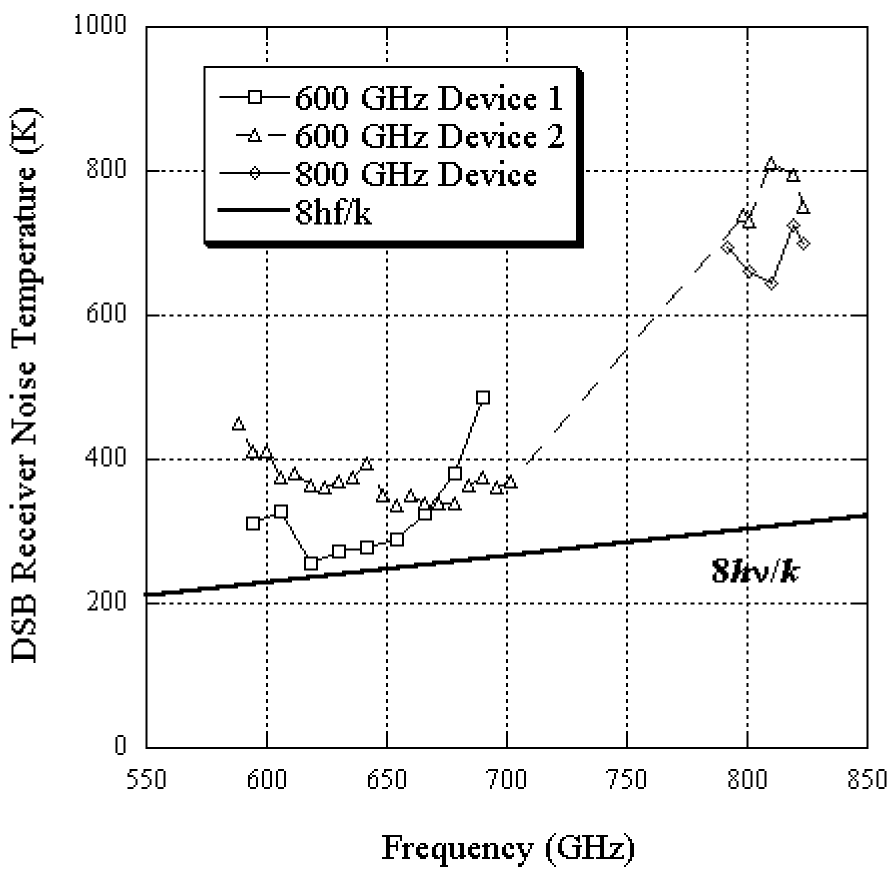

Fig. 5 Double-side-band receiver noise temperature measured for two 600 GHz and one 800 GHz NbTiN mixer chips.

The frequency response of the NbTiN mixers has also been measured for both 600 and 800 GHz chips. Fig. 5 shows the measured noise temperature as a function of frequency for two 600 GHz chips and one 800 GHz chip. The results show that a sensitivity of about 10 *hn/k* is achieved in the 600 GHz band.

The receiver is also extremely stable and its performance is highly repeatable. Once the system is well aligned, amplitude fluctuations of the IF power output are very small over time scales of minutes. In a typical hot/cold load measurement, the measured Y-factor is repeatable to better than 1%. From the direct power measurements, we believe that the receiver amplitude stability is < 0.004. This is comparable to SIS receivers, and far better than most other HEB receivers.

V. Field Testing

Last year, we deployed an NbN based HEB receiver at the Submillimeter Telescope on Mount Graham, Arizona for use primarily in the 800 – 900 GHz atmospheric window. That receiver was used in the first ground-based heterodyne detection of a celestial source above 1 THz [8]. This year, we have substituted the NbN mixer with an 800 GHz NbTiN HEB mixer. According to measurements taken at the telescope, the NbTiN receiver has a noise temperature of about 850 K at 810 GHz, similar to the performance of the NbN based HEB receivers installed on the telescope during the two previous years [6,9]. To demonstrate the true heterodyne performance of this NbTiN receiver, we have measured the emission spectra of CO (7—6) in an astronomical source, IRC+10216. The observed spectrum is recorded in Fig. 6.

VI. Conclusion

NbTiN thin films deposited on crystalline quartz substrate with an AlN buffer layer have successfully been used in a phonon-cooled HEB mixer. The 3-dB IF bandwidth of this mixer is about 2.5 GHz. The mixer chips have been incorporated in a fixed-tuned waveguide receiver which exhibits very good noise performance in the 600 and 800 GHz frequency bands, close to 8 *hn/k* at 630 GHz. This receiver has good gain stability and is currently being used for astronomical observations at the Sub-Millimeter Telescope in Arizona.

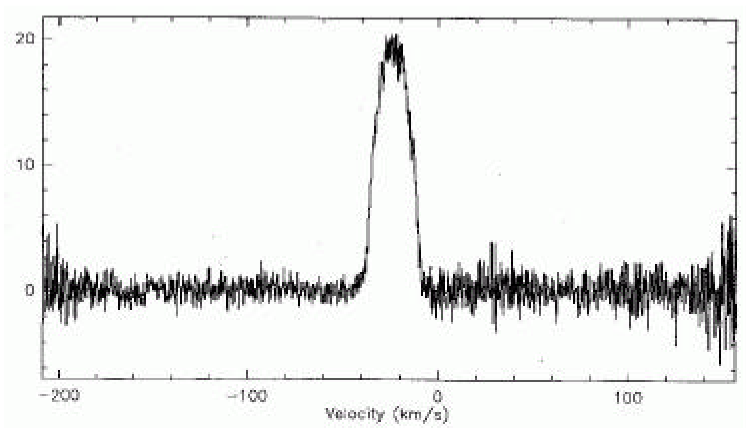

Fig. 6 CO (7—6) emission spectrum recorded by the NbTiN HEB receiver at a signal frequency of 806.65 GHz. The astronomical source, IRC+10216, was at an elevation angle of 69 degrees during the observation. The total system noise temperature was estimated to be 7700 K and the atmospheric opacity at zenith was 1.2. The integration time was 4.2 minutes.

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