Development of 1.5 THz Waveguide NbTiN HEB Mixers

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***Abstract*— We present results on the design, fabrication, and measurement of 1.5 THz waveguide niobium titanium nitride (NbTiN) superconducting hot electron bolometer (HEB) mixers. The NbTiN HEB mixer element is made from a 12 nm thick NbTiN thin film deposited on a crystalline quartz substrate at room temperature. The Fourier transform spectrometer (FTS) measurement shows that the response of the HEB mixer is centered near 1.3 THz with a bandwidth of about 400 GHz. The uncorrected DSB receiver noise temperature is measured to be 1700 K at 1.5 THz, whereas the mixer noise temperature is 1000 K after correction of quasi-optical and IF chain losses. The required LO power absorbed in the HEB mixer is evaluated to be 340 nW by using an isothermal technique. The IF gain bandwidth is supposed to be about 1.3 GHz or higher. The present results show that good performance can be obtained for the NbTiN HEB mixer even with a relatively thick film (12 nm) fabricated at the room temperature.**

***Index Terms*—Terahertz, Hot electron bolometer mixer, NbTiN film, Receiver noise temperature.**

I. INTRODUCTION

Superconducting mixers play a key role in astrophysics and atmospheric science in the terahertz region, which contains unique spectral lines of ions, atoms, and molecules that profoundly depict fundamental astrophysical and atmospheric processes. In particular, low noise superconductor-insulator-superconductor (SIS) mixers have realized high sensitive astronomical observations on ground-based, airborne, and space-based telescopes [1-2]. However, its sensitivity degrades drastically owing to the abrupt increase of the loss of superconducting film above the energy gap frequency (~700 GHz for niobium, for instance). Superconducting hot electron bolometer (HEB) mixers have matured as the most sensitive heterodyne detectors at frequencies between 1.2 to 6 THz [3-8]. In principle, the RF bandwidth of HEB mixers is not limited by the superconducting energy gap. The superconducting HEB mixers can be operated from millimeter wave up to far infrared without degradation in performance, and show good performance of double-sideband (DSB) receiver noise temperature approaching six times the quantum limit ($6h\nu/k$) with the required local oscillator (LO) power of only a few tens of nanowatt (nW). Therefore, they are being employed for astronomy and atmospheric applications as sensitive detectors to observe faint signals in the THz region [9-11].

Currently the state-of-the-art phonon-cooled HEB mixers are fabricated from a thin niobium nitride (NbN) film. However, the niobium titanium nitride (NbTiN) HEB mixer is an alternative option as well for the HEB mixers [12-13], since its physical and chemical properties are quite similar to those of NbN. In contrast to the NbN film, the NbTiN film can readily be fabricated on quartz substrate, and hence, it can readily be used for a waveguide mixer, which gives a well-defined beam pattern. In spite of this merit, studies on the NbTiN HEB mixers have so far been limited in comparison with the NbN mixers. In this paper, we present our continuous efforts to realize a 1.5 THz waveguide NbTiN HEB receiver for ground-based astronomical observations [14-15].

II. WAVEGUIDE COUPLED NBTIN HEB MIXER

A. Fabrication

Our HEB device is based on an NbTiN superconducting thin film that is deposited on a Z-cut crystalline quartz substrate by the reactive sputtering of an NbTi (weight ratio of Nb:Ti = 4:1) alloy target in a mixture of Ar and N_2 gas at room temperature. By employing an RF plasma assisted sputtering system, the NbTiN film is deposited in a low pressure condition (0.4 Pa) to ensure high film quality.

Fig. 1 shows a sketch of the HEB structure. In the HEB device fabrication, the deposition of the microbridge consisting of a 12 nm NbTiN film and the contact pads (2 nm Ti and 40 nm Au bilayer) on the crystalline quartz substrate is carried out without breaking vacuum. This sputtering process is so-called *in situ* technique, which avoids the unfavorable

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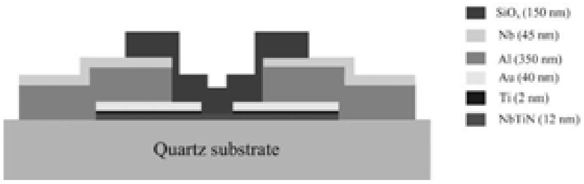
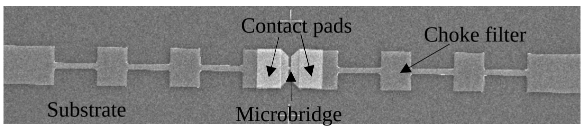


(a)



(b)

Fig. 1. (a) Cross section view of the microbridge, contact pads, choke filter, and passivation layer. (b) Scanning electron microscope (SEM) micrograph of the fabricated HEB element.

formation of an oxide layer on the NbTiN film surface. The choke filter structure is formed by a lift off process using a positive photo resist mask and *in situ* deposition of 350 nm Al and 45 nm Nb. The microbridge length is defined by a positive electron-beam resist mask and subsequent inductively coupled plasma (ICP) etching. As the last step, the microbridge area is covered by an SiO_x (1< x <2) passivation layer for protection. Since it is very difficult to measure the NbTiN film thickness with high accuracy, the film thickness is estimated as a product of the sputtering time and the deposition rate. The NbTiN film thickness is confirmed to be proportional to the sputtering time for films with thickness of a few tens nm. The dimensions of the NbTiN microbridge investigated in this paper are 0.3 μm in length and 1.5 μm in width. The cross section view of the HEB structure is shown in Fig. 1 (a), and a scanning electron microscope (SEM) micrograph of the HEB device in a front view is shown in Fig. 1 (b).

B. *DC characterization and analysis*

Here we discuss DC properties that indicate the quality of

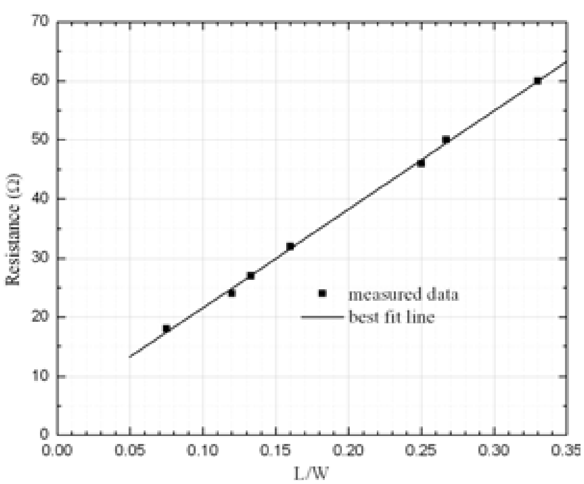


Fig. 2. Measured normal state resistance at 15 K ($R_{15\,K}$) as a function of the ratio of the microbridge length to the width (L/W). The square resistance ($R_{\square,\,15\,K}$) at 15 K is evaluated to be about 170 Ω from the slope of the best fit line.

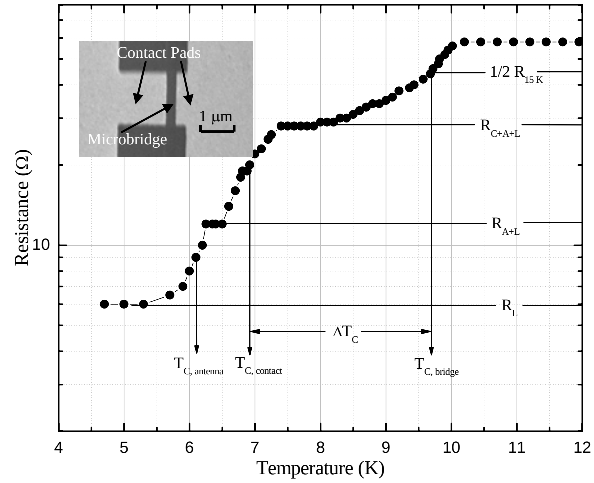


Fig. 3. Resistance versus temperature curve of the measured HEB device, R_{C+A+L} is the resistance above $T_{c,\,contact}$ with $T_{c,contact}$ the critical temperature of the stack layer containing the contact pads and antenna structure on top of the NbTiN film, R_{A+L} the resistance of the antenna and leads, $T_{c,bridge}$ the critical temperature of the NbTiN microbridge, R_L the leads resistance, and ΔT_C the transition width. Inset: zoomed SEM micrograph of the NbTiN microbridge between the contact pads.

the devices. Fig. 2 shows the measured normal state resistance at 15 K ($R_{15\,K}$) as a function of the ratio of microbridge length to width (L/W) for different-sized devices, where L is the microbridge length and W the microbridge width. The $R_{15\,K}$ values clearly show a linear dependence on L/W, demonstrating good uniformity of the deposited ultra-thin NbTiN film. The linear relation can be represented as $R_{15\,K} = R_{C+A+L} + R_{\square,15\,K} \times (L/W)$, where $R_{\square,15\,K}$ is the square resistance at 15 K, and R_{C+A+L} is the resistance of the contact pads and the antenna structure of the mixer element including contact resistance among them as well as contribution from leads. From Fig. 2, the $R_{\square,15\,K}$ is evaluated to be about 170 Ω. In order to match waveguide coupled RF circuit, we select a device with proper $R_{15\,K}$ close to the waveguide embedding impedance. The device resistance versus temperature (R-T) curve is shown in Fig. 3. The R-T curve shows three superconducting transitions. $T_{c,contact}$ is due to the proximitized NbTiN film under the contact pads as a result of the superconducting proximity effect between the NbTiN film and the normal contact pads of the Au/Ti bilayer. $T_{c,bridge}$ is caused by the NbTiN microbridge itself, which is defined as the temperature at which the resistance becomes a half of the R_{15K}. $T_{c,antenna}$ is supposed to originate from the antenna structure composed of Al/Nb bilayer on top of the NbTiN. The measured $T_{c,bridge}$ is 9.7 K with a transition width ΔT_C of 2.9 K.

C. *Design of waveguide coupled RF circuit and characterization*

The configuration of the 1.5 THz NbTiN HEB element is designed with the aid of high frequency structure simulator (HFSS) software. The waveguide has a 180 μm width and a 70 μm height. The mixer's RF choke filter is designed on the basis of a 42-μm-wide and 23-μm-thick quartz substrate (ε_r = 4.65), which is accommodated in a 64-μm square slot. A detail of the HFSS calculation is described elsewhere [15].

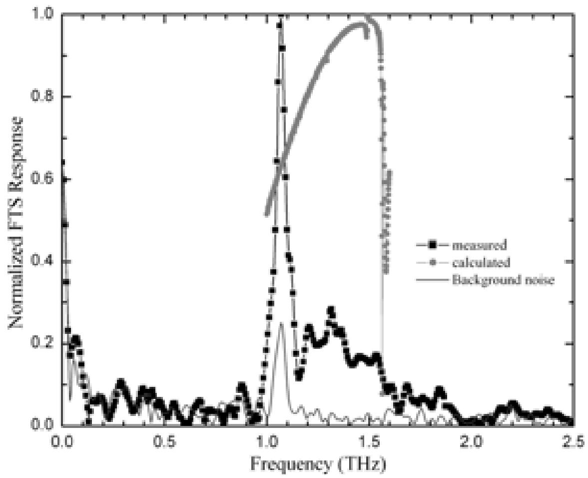


Fig. 4. Normalized direct detection response of the waveguide coupled HEB mixer measured after correction of optical components with a Fourier transform spectrometer. The simulated normalized response is also included for comparison. Note that the peak frequency appearing 1.07 THz is caused by the background noise in FTS measurement room.

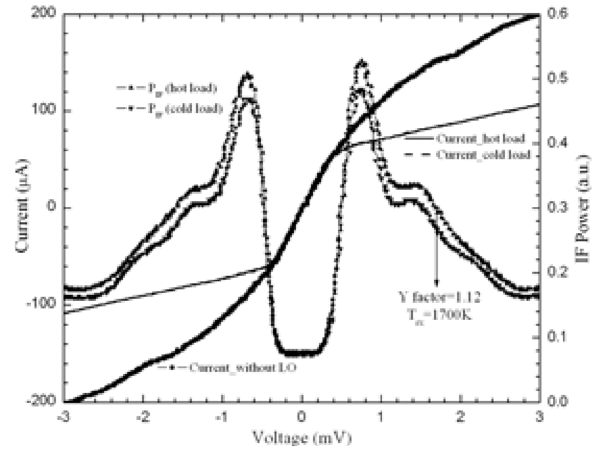


Fig. 5. Current-voltage curves of HEB mixer with and without LO at 1.5 THz, and receiver IF output powers P_{IF} (hot) and P_{IF} (cold) corresponding to the hot (295 K) and cold (77 K) loads respectively as a function of the bias voltage at the optimum LO pumping level. The maximum Y-factor (P_{IF} (hot) / P_{IF} (cold)) is 1.12, which corresponds to the receiver noise temperature of 1700 K.

The experimental characterization of the waveguide coupled mixer response is performed by an evacuated Fourier transform spectrometer (FTS) system with the HEB chip accommodated in the waveguide block. The signal beam of the FTS is collimated to the mixer horn by an elliptical mirror. Fig. 4 shows the measured FTS response of the HEB after correction for the frequency dependent transmission of the optical components of the FTS, including the beam splitter in the FTS and the vacuum window of the 4 K cryostat. The simulated response of the waveguide embedding circuit is shown in the same figure as well. The measured peak frequency appearing at 1.07 THz is due to the background noise of measurement environments. Regardless of the interference noise, the maximum FTS response is found to locate at 1.3 THz, which has a small deviation from the design frequency of 1.5 THz. The 0.2-THz frequency shift is probably caused by imperfect waveguide machining.

III. MEASUREMENT SETUP

The characterization of the HEB mixer receiver is performed by a quasi-optical setup, which is similar to that reported in the previous paper [15]. The HEB mixer chip is housed in the waveguide mixer block, which is mounted on the cold plate of a GM two-stage 4 K close-cycled refrigerator. The LO source is a 1.4-1.5 THz multiplier chain [16], which provides a peak output power of 20 μW while operated at 1.47 THz. The output horn of the LO source is a diagonal feed horn designed for 1.5 THz. The LO beam is collimated with a parabolic mirror, and is combined with the RF signal of the blackbody radiation from a slab of Eccosorb at 295 K (hot load) and 77 K (cold load) through a 6 μm thick Mylar beam splitter.

The HEB mixer's IF output is connected via a bias-tee to a cooled isolator and a 0.9-1.3 GHz low noise amplifier, which is followed by a room temperature amplifier chain. The latter consists of two amplifiers, a directional coupler with through output followed by a spectrum analyzer, and coupling output filtered by a band pass filter, detected by a square law direct detector, and recorded by computer. The band pass filter has a bandwidth of 200 MHz at the center frequency of 1.1 GHz. The IF amplifier chain connected to the spectrum analyzer provides a gain of 80 dB with a noise temperature of 12 K.

IV. MEASUREMENT RESULTS

A. Receiver noise temperature

We have employed the conventional Y-factor method to measure noise temperature of the waveguide NbTiN superconducting HEB mixer. Fig. 5 shows the measured IF output power and the bias current corresponding to the hot and cold loads as a function of the bias voltage at the optimum LO pumping level. The maximum Y factor of 1.12 is achieved at 1.5 THz, when the HEB is operated at the bias voltage of 1.7 mV and the current of 83 μA. We obtain the lowest receiver noise temperature of 1700 K based on the measured Y factor using a Callen and Welton temperature definition [17]. The measurement is performed at the IF frequency (1.1 GHz) at which the mixer gives the best sensitivity. This receiver noise temperature is comparable to those of the waveguide NbTiN HEB mixer receivers so far reported by other groups; 1900 K @ 1.3 THz [12] and 1600 K @ 1.5 THz [18]. We evaluate the required LO power P_{LO} by using an isothermal technique [19]. The LO power requirement at the optimum bias point is evaluated to be 340 nW for the HEB mixer with a 12 nm thick NbTiN film. We can reduce the required LO power by reducing the mixer size. The direct detection effect is not obvious, because the bandwidth of the waveguide HEB mixer is quite narrow according to the FTS measurement results.

We have also confirmed the heterodyne mixing by introducing a small output power of another 1.5 THz frequency source as the RF input. The heterodyne beat signal

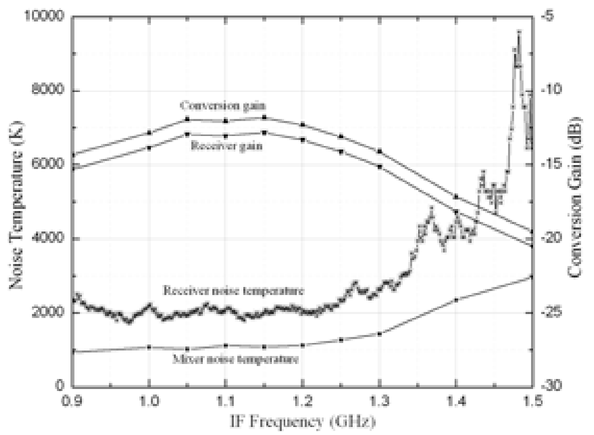


Fig. 6. Measured receiver noise temperature and conversion gain. The mixer noise temperature and conversion gain are obtained after correcting losses of the quasi-optical path and the IF amplifier chain.

is recognized easily in the IF output by a spectrum analyzer.

B. *Intermediate frequency gain bandwidth*

We have measured the DSB receiver conversion gain of the waveguide NbTiN superconducting HEB mixer with a U-factor technique [20] by measuring the hot and cold load output powers as a function of frequency. Fig. 6 shows the measured receiver and mixer noise temperatures and conversion gains at the optimum operating point. The HEB mixer noise temperature and conversion gain are obtained after correcting the losses in the quasi-optical path and the IF amplifier chain. Since the bandwidth of the IF amplifier chain is 0.9-1.3 GHz, the accurate receiver and mixer gains cannot be obtained below 0.9 GHz and above 1.3 GHz. Nevertheless, we can say that the IF gain bandwidth of the HEB mixer is about 1.3 GHz or higher, even though for a 12 nm thick NbTiN film.

C. *Stability*

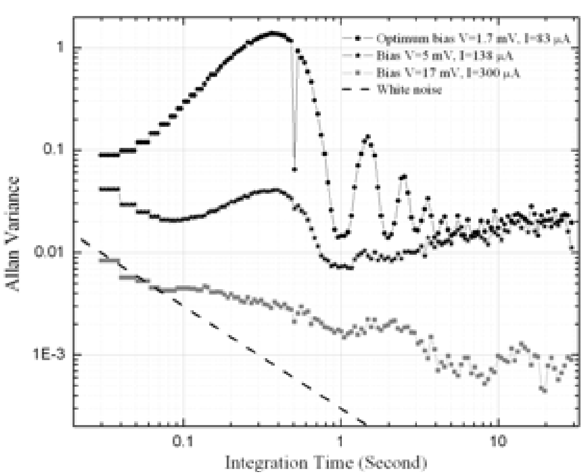


Fig. 7. Allan variance of the NbTiN HEB receiver operated at 1.5 THz obtained in a 200 MHz bandwidth at the optimum bias voltage and higher DC biases. The theoretical white behaviour and stability behaviour of the HEB mixer driven into normal state by high DC bias are included for comparison.

To evaluate the receiver system stability, we have measured, at the optimal operating conditions, the Allan variance [21] of the receiver system. We have performed the Allan variance measurement of the receiver system by monitoring the IF output power as a function of time. The bandpass filter is centered at 1.1 GHz with a 200 MHz bandwidth. In Fig. 7, the Allan variance is measured at the optimum bias point and higher DC biases. It is very clear that the 1 sec period temperature fluctuation and mechanical vibration caused by 4 K close-cycled refrigerator has distinct effect on the Allan variance. Its influence gradually decreases with DC bias voltage, but still exists at high DC bias (17 mV). The Allan time is estimated to be around 1 sec, even if the 1 sec period fluctuation is excluded with a mathematical analysis. This may reflect some instabilities in the IF amplifier chain.

V. CONCLUSION

In summary, we have successfully realized a terahertz heterodyne receiver system based on a superconducting NbTiN HEB mixer. The superconducting NbTiN ultra-thin film deposited on a crystalline quartz substrate at room temperature is used for the HEB mixer. We employ *in situ* fabrication of the NbTiN layer and the Au/Ti contact pads. The waveguide RF embedding circuit is designed by an HFSS software, and is characterized with an evacuated FTS in combination with the NbTiN HEB mixer. We have measured an uncorrected DSB receiver noise temperature to be 1700 K at 1.5 THz. The mixer noise temperature of 1000 K is obtained after the correction of losses of quasi-optical path and IF amplifier chain. The IF gain bandwidth is measured to be about 1.3 GHz or higher at the optimum operating point. The LO power requirement of the HEB mixer is evaluated to be 340 nW for a $1.5\times0.3\ \mu m^2$ microbridge area. The Allan time is observed to increase with DC bias, and estimated to be about 1 sec while excluding the effect of intrinsic 1 sec period fluctuation by mathematical analysis.

It should be noted that the above performance is obtained based on a 12 nm NbTiN film which is thicker than that used by other groups (a few nm) for the phonon-cooled mixers, where the phonon-cooling is less effective for a thicker film. In contrast to conventional fabrication processes of phonon-cooled HEBs, we have employed an *in situ* process in the HEB fabrication, which ensures good transparency of hot electrons between the NbTiN film and Ti/Au contact layer. It would make the diffusion-cooling process work to some extent in addition to the phonon-cooling process [22]. Although this was pointed out for our 0.8 THz HEB mixers [15], the same effect has also been confirmed in the present 1.5 THz mixer. The attractive advantage of the diffusion-cooled HEBs is that wideband IF gain bandwidth can be achieved with a reasonable noise performance [23]. Therefore, in our HEBs, the existence of both of phonon- and diffusion-cooling mechanisms due to *in situ* process, makes the HEB receiver noise temperature be as low as 1700 K and a 1.3 GHz or higher IF gain bandwidth even with a 12 nm thick NbTiN film.

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