Development of THz Waveguide NbTiN HEB Mixers

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Abstract—In this paper, we present the development of the waveguide Niobium Titanium Nitride (NbTiN) superconducting hot electron bolometer (HEB) mixers, cryogenically cooled by a 4-K close-cycled refrigerator. The NbTiN thin film is formed on a crystalline quartz substrate by sputtering an NbTi target with the Ar and N_2 gas at room temperature. The HEB mixer element is fabricated by using the 12 nm NbTiN film, and is mounted on a waveguide block. Measurement of a Fourier transform spectrometer shows that the response of the mixer is centered near 810 GHz with a bandwidth of about 500 GHz. The uncorrected DSB receiver noise temperature is measured to be 500 K, and the noise bandwidth is to be 1.4 GHz at 810 GHz. The present result shows that a good noise 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.**

I. INTRODUCTION

Superconducting hot electron bolometer (HEB) mixers have matured as the most sensitive heterodyne detectors in the frequency range from 1.5 to 6 THz [1]–[6], where the performance of superconductor-insulator-superconductor (SIS) mixers degrades drastically owing to the abrupt increase of the losses of superconducting films above the energy gap (~700 GHz for niobium, for example). The superconducting HEB mixers show double-sideband (DSB) receiver noise temperature approaching six times the quantum limit ($6h\nu/k$) and require the local oscillator (LO) power of only a few tens of nanowatt. Therefore, they are employed in astronomy and atmospheric science as sensitive detectors for passive observations of faint signals in the THz region [7]–[9]. In particular, state-of-the-art phonon-cooled HEB mixers using a thin niobium nitride (NbN) film attract a great deal of attention because of their high sensitivity and broad intermediate frequency (IF) bandwidth. However, the niobium titanium nitride (NbTiN) HEB mixer is promising as well in the THz region, because the NbTiN film has physical and chemical properties similar to the NbN film. In contrast to the NbN film, the NbTiN film can readily be fabricated on a quartz substrate, and hence, it can be used for a waveguide mixer, which gives a well-defined beam pattern. This is an important merit for astronomical applications. For instance, Wiedner et al. has recently observed the CO *J*=13-12 emission line (1.5 THz) with the waveguide NbTiN HEB mixer receiver equipped on the APEX telescope [10]. However, efforts and experiences have still been limited for the NbTiN HEB mixers. We here present the design, fabrication, and RF performance measurement of our waveguide NbTiN HEB mixer in detail.

II. DEVICE FABRICATION AND DESIGN

The NbTiN thin film is deposited on a Z-cut crystalline quartz substrate by reactive sputtering of an NbTi (weight ratio of Nb:Ti = 4:1) alloy target with the N_2/Ar gas at room temperature. By using the RF plasma assisted sputtering system, the NbTiN film can be deposited in a low pressure condition (0.4 Pa), which would improve the quality of film. According to Maezawa et al. [11], the characteristics of the NbTiN film depend on the N_2 flow rate and the total pressure. The critical temperature T_c of the NbTiN thin film is sensitive to the N_2 flow rate, whereas the stress of film relies on the

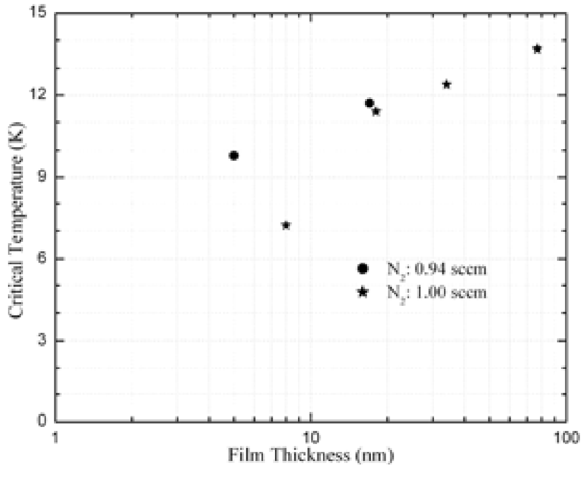

Fig. 1 Thickness dependence of the critical temperature of the NbTiN film for two cases of the N_2 flow rate.

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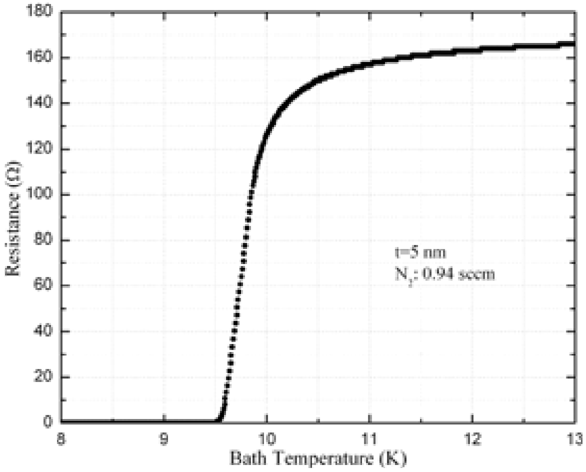

Fig. 2 Resistance-temperature curve of the 5 nm thick NbTiN film with the N_2 gas flow of 0.94 sccm.

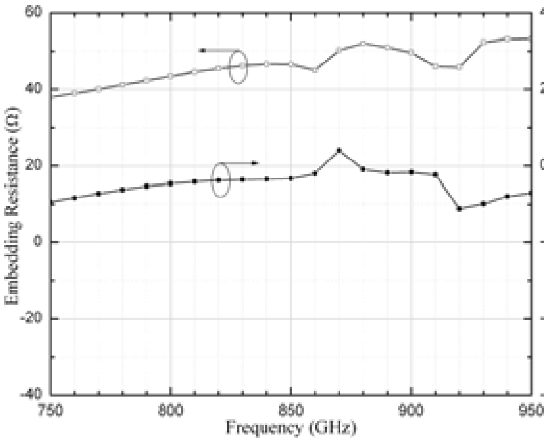

Fig. 4 Embedding impedance as a function of frequency, simulated for the 810 GHz NbTiN waveguide HEB mixer.

total pressure. Indeed, we find that a slight change in the N_2 flow rate sensitively affects T_c, particularly for thin film (< 10 nm). We carefully optimized the N_2 flow rate, and finally found the best value to be 0.94 sccm. The thickness dependence of T_c for two cases of the N_2 flow rate is shown in Fig. 1, as an example. The T_c value for the 5 nm film is 9.8 K at the best condition. In this case, the resistance-temperature (*R*-*T*) curve shows a smooth superconductive transition, as shown in Fig. 2. Since it is very difficult to measure the thickness of ultra thin NbTiN film with a high accuracy, the film thickness is estimated as the product of sputtering time and deposition rate. The NbTiN film thickness is confirmed to be proportional to the sputtering time for films with thickness of a few tens nanometer. Although our deposition process is carried out at the room temperature unlike the other groups [12], a good quality film which deserves fabrication of the HEB mixers can be obtained.

In an HEB device fabrication, the NbTiN and Ti/Au layers are successively deposited on the crystalline quartz substrate without breaking vacuum. This is essential for ensuring a good contact between the two layers without suffering from natural oxidation of the NbTiN film surface. The active area of the HEB mixer is defined by the electron beam lithography and the ICP (inductively coupled plasma) RIE (reactive ion etching) system. A typical size of the microbridge structure is about 0.2 μm long and 2 μm wide. In the present stage, we employ a rather thick NbTiN film of 12 nm for easy fabrication. The fabricated HEB mixer has a normal state resistance of 25 Ω, a critical current of higher than 500 μA at 4.2 K, and the critical temperature of 9.8 K. Fig. 3 shows a SEM micrograph of an example of our HEB mixers.

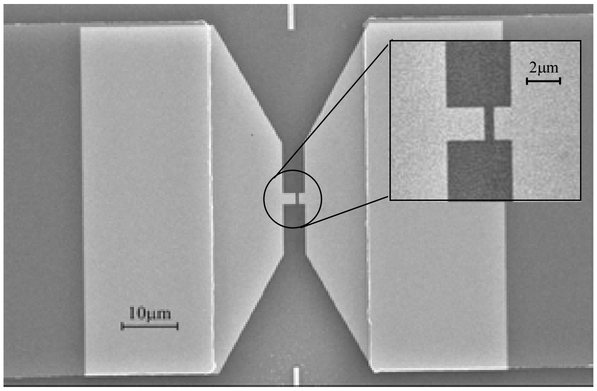

Fig. 3 SEM micrograph of a waveguide NbTiN HEB mixer.

The configurations of the NbTiN HEB mixer chip are designed with the aid of the High Frequency Structure Simulator (HFSS) software. For the 810 GHz mixer, the waveguide with 304-μm width and 105-μm height is chosen to cover the frequency range of 780-950 GHz. The mixer's RF choke filter is designed on the basis of a 95-μm-wide and 44-μm-thick quartz substrate ($\varepsilon_r = 4.65$), which is accommodated in a slot of 105-μm square. In the HFSS calculation, we take into account of the real microbridge structure (0.2 μm long by 2 μm wide) as the device's feed point. Embedding impedance of the mixer looked at the feed point is calculated by HFSS as

$$Z_{emb} = Z_0 \times \frac{1+\Gamma}{1-\Gamma}, \qquad (1)$$

where Γ is the computed complex reflection coefficient at the feed point and Z_0 stands for port impedance. The calculated embedding impedance is plotted in Fig. 4, which shows a good RF impedance matching between the RF circuit and the NbTiN HEB mixer.

To confirm the design of RF coupling circuit, the spectral response of the NbTiN HEB mixer has been measured with a Fourier transform spectrometer (FTS) by using the mixer element as a direct detector. For this purpose, the mixer is operated at an elevated bath temperature close to the critical temperature without introducing LO power. The mixer shows a response centered near 810 GHz with the bandwidth of about 500 GHz (Fig. 5), which confirms a good RF coupling.

III. MEASUREMENT SETUP

The layout of the measurement setup is shown in Fig. 6. The HEB mixer chip is housed in a waveguide mixer block, which is mounted on a cold plate of a GM two-stage 4-K close-cycled refrigerator. A Gunn oscillator, operating at

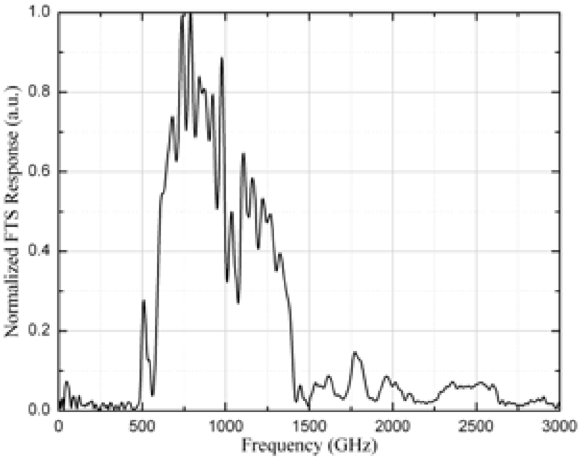

Fig. 5 Spectral response of the HEB mixer as measured by an FTS in direct detection mode. Note that the standing wave caused between the FTS and the 4-K cryostat can be seen in the spectrum. A dip around 1 THz may be due to the water absorption.

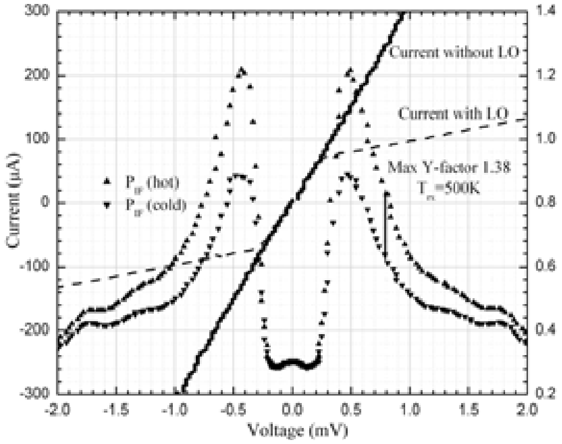

Fig. 7 Current-voltage curves of HEB mixer with and without LO at 810 GHz, and receiver IF output powers P_{IF} (hot) and P_{IF} (cold) corresponding to the hot (295 K) and cold (77 K) loads respectively as a function of bias voltage at optimum LO pumping level. The maximum Y-factor (P_{IF} (hot) / P_{IF} (cold)) is 1.38, which corresponds to the receiver noise temperature of 500 K.

90 GHz, followed by two frequency triplers, provides the LO power at a frequency of 810 GHz. The blackbody radiation from a slab of Eccosorb at 295 K (hot load) and 77 K (cold load) is used as an RF signal. The LO signal is collimated with a parabolic mirror, and is further combined with the RF signal by a beamsplitter. The combined signal passes through a parabolic mirror, a 7.5 μm thick Kapton vacuum window, and two Zitex G106 infrared filters mounted on the 50 K shield, and is finally focused into the diagonal horn of the mixer block by a parabolic mirror on the 4-K cold plate of the cryostat.

The IF output signal with the frequency range of 0.9-1.3 GHz goes through a bias-tee and an isolator to the cryogenic amplifier, and it is further amplified by a room-temperature amplifier chain. The latter consists of two amplifiers and a band pass filter. The IF power is finally measured by a square-law detector. The band pass filter has a bandwidth of 200 MHz at the center frequency of 1.1 GHz. The entire IF chain has a gain of 87 dB and a noise temperature of 9.5 K.

IV. RESULTS AND DISCUSSIONS

We have used the conventional Y-factor method to measure the noise performance of the waveguide NbTiN superconducting HEB mixer. Fig. 7 shows the measured IF output powers corresponding to the hot and cold loads as a function of the bias voltage at optimum LO pumping level. The minimum receiver noise temperature of 500 K is obtained at 810 GHz with the bias voltage and current of 0.8 mV and 93 μA, respectively. This is comparable to the results of the other groups published previously [13]. Even at 650 GHz, the receiver noise temperature is 640 K, being consistent with a wideband response of the mixer (Fig. 5).

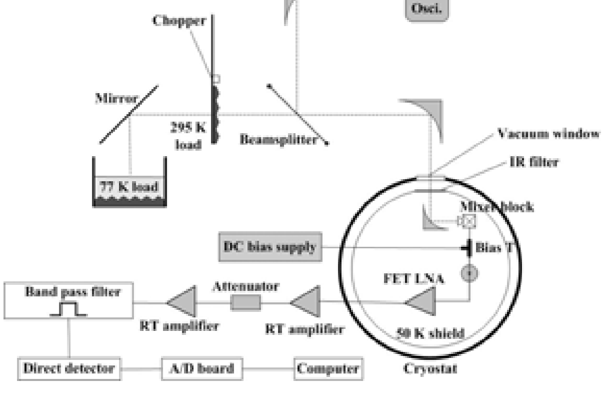

Fig. 6 Schematic of measurement setup.

We have also measured the DSB receiver conversion gain of the waveguide NbTiN superconducting HEB mixer using a U-factor technique [14], as shown in Fig. 8. The HEB mixer gain is obtained after correcting the losses in the quasi-optical path and the IF amplifier chain. Since the bandwidth of IF amplifier chain is 0.9-1.3 GHz, the accurate receiver and mixer gains cannot be obtained below 0.9 GHz. The IF gain bandwidth of the mixer is supposed to be around 1.2 GHz, and the measured receiver noise bandwidth is about 1.4 GHz.

In summary, we have successfully fabricated and characterized terahertz superconducting NbTiN HEB mixers. An uncorrected DSB receiver noise temperature is measured to be 500 K at 810 GHz, and the calibrated mixer noise temperature is 260 K after the correction of the losses of quasi-optical path and IF amplifier chain. The measured noise bandwidth is about 1.4 GHz, and the IF gain bandwidth is about 1.2 GHz. Although our mixer employs a relatively thick NbTiN film (12 nm) deposited at the room temperature, the performance obtained is comparable to those reported previously.

In particular, it seems worth stressing that the above performance is obtained with the 12 nm film which is thicker than those used by other groups (a few nm) for the phonon-cooled mixers. It is well known that the phonon-cooling is less effective for a thicker film [15, 16]. In fact, the escape time of phonons into substrate $\tau_{ph\text{-}s}$ is longer than the phonon-electron interaction time $\tau_{ph\text{-}e}$ for a 12 nm thick film, giving unfavourable condition as HEB mixers. Considering our HEB mixer fabrication employs an in-situ deposition of the NbTiN film and the Ti/Au electrodes, the good contact between the NbTiN and Au films should be realized. Because of this reason, the diffusion-cooling mechanism may also work to some extent in addition to the phonon-cooling mechanism, which helps to improve the performance [17]. Further experiments for the different-sized mixers are needed to confirm it.

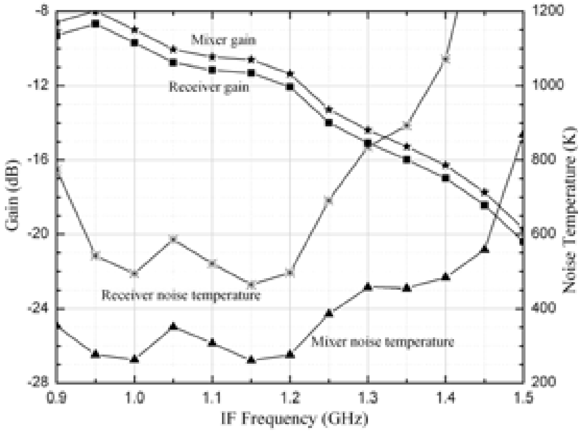

Fig. 8 Measured receiver noise temperature and conversion gain. The mixer noise temperature and gain are obtained after correcting the losses of the quasi-optical path and the IF amplifier chain.

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