Fabrication and Noise Measurement of NbTiN Hot Electron Bolometer Heterodyne Mixers at THz Frequencies

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Abstract

The paper reports the latest development and the measured results of NbTiN hot electron bolometer mixers at THz frequencies. The devices are based on 4-7 nm thin NbTiN films, which were deposited by reactive magnetron sputtering of NbTi target in an Ar/N_2 atmosphere, on heated high-resistivity Si substrates over a 20 nm thick AlN buffer layer. The quality parameters of the film are transition temperature and normal-state resistivity, which were optimized by varying the sputtering parameters. The resistivity and the critical temperature of the films are about 400 $\mu\Omega$cm and 9 K, respectively. Bolometers (4 μm wide and 0.7 μm long), integrated with logarithmic spiral antennas are fabricated. Mixer noise performance is tested in a quasi-optical receiver in 1.5-4 GHz IF band. The DSB receiver noise temperature of 700 K, 1100 K and 3000 K is obtained at 0.7, 1.6 and 2.6 THz LO frequencies, respectively.

1 Introduction

Currently superconducting hot electron bolometers (HEBs) are the most competitive devices for heterodyne detection in THz range [1]. Phonon-cooled NbN HEB mixer has become a relatively mature and reliable technology [2, 3]. It requires less than 1 μW of LO power [4] and offers about 1 K/GHz DSB receiver noise temperature up to 2.5 THz with 5-6 GHz IF bandwidth [5, 6, 7]. Noise measurements up to 5 THz have been reported [8]. There are many active projects, which are planned to benefit from this technology in ground based (TREND [9], APEX [10]), airborne (SOFIA [11]) and spaceborne (Herschel [12]) observatories. HEB's noise performance above 2 THz will certainly improve with further development of THz antennas and waveguide techniques. Nevertheless, extension of the IF bandwidth and reduction of LO power requirements calls for new materials and approaches in HEB devices. Among others, NbAu bilayer HEBs [13], Ta HEBs [14] and 2-DEG semiconducting HEBs [15, 16] can be mentioned. Recently NbTiN thin films HEB mixers have been successfully fabricated and tested at 600 GHz and 800 GHz with DSB noise temperature of 270 K and 650 K at 1.5 GHz IF [17]. The gain roll-off frequency has been observed at 2.5 GHz (the film thickness was quoted to be 4 nm). Gain bandwidth measurements of NbTiN HEB mixers as a function of bias voltage can be also found in [18]. So far, Neither noise temperature nor noise bandwidth measurements at THz frequencies have been reported.

2 Device Fabrication

Bulk Niobium-titanium nitride (NbTiN) has a critical temperature of 16-17 K and a resistivity of around 90 $\mu\Omega$cm [19]. The properties of NbTiN show a strong dependence on the magnetron sputtering conditions and the film quality decreases as the film gets thinner. Thin (4-7 nm) NbTiN films are deposited on high resistive silicon substrate with 20 nm of AlN buffer layer, by DC reactive magnetron sputtering using a $Nb_{78\%}Ti_{22\%}$ alloy sputtering-target (99.9% purity) in a mixture of Ar and N_2. The substrate was heated by a radiative heater below the substrate up to 400 °C during deposition. The typical sputtering conditions are listed in Table 1. The quality parameters of the film are transition temperature and normal-state resistivity, which were optimized by varying the sputtering parameters. Table 2 summarizes some of the parameters of four different films, which were chosen for fabrication of four batches of HEB devices. About 50 bolometers, integrated with different double slot and log

Parameters	Value
Base pressure	8.9×10^{-8} mbar
Gas flow rates	Ar 40 sccm N_2 10 sccm
DC power	300 W
Background pressure	0.63 Pa
Substrate temperature	400 °C
Deposition rate	0.5 nm/sec
Target-substrate distance	8 cm

Table 1: Typical sputtering condition for NbTiN film

Film ID	thickness (nm)	Deposition Temp. (°C)	Critical Temp. (K)
CCN8-11	5-6	200	8
CCN8-1	6-7	375	7
CCN8-5	6-7	375	9
CCN8-15	4-5	400	10

Table 2: NbTiN films

periodic spiral antennas were fabricated in each batch. The fabrication is done by three consecutive electron beam lithography steps followed by metallization and lift off, where small contact pads, antenna and the large contact pads are patterned. 5 nm Ti followed by 80 nm of Au is deposited for small contact pads. The antenna and large pads are made from 5 nm of Ti and 200 nm Au. Then a resist mask is defined over the bolometer bridge by one more lithography step. This is to protect the NbTiN film in the bolometer bridge during the ion milling. In the last step the NbTiN is etched away using Ar ion milling from the whole wafer except the bolometer bridge and under the antenna and pads.

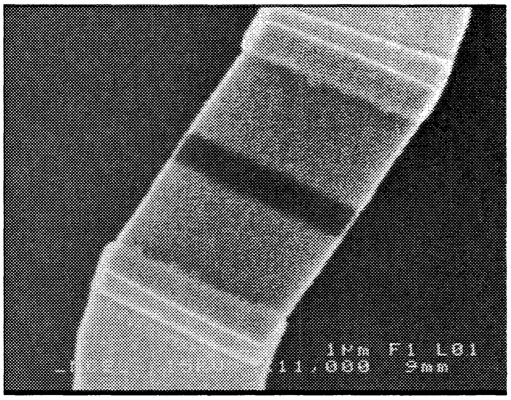

Figure 1: SEM picture of a 4 μm wide 0.7 μm long bolometer in the center of the spiral antenna.

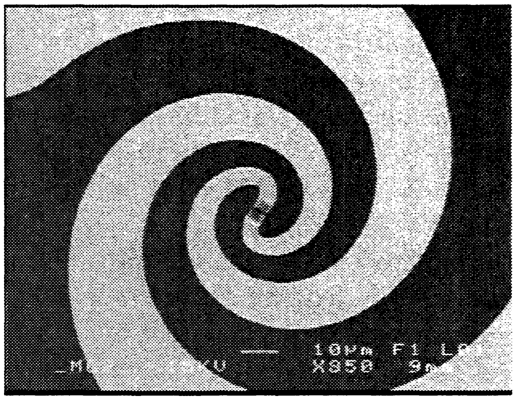

Figure 2: SEM picture of a HEB integrated with a log periodic spiral antenna.

The scattering of the measured dc parameters (room temperature resistance and critical current) of devices within a batch is very small. This indicates that the film deposition have been quite homogeneous over the whole wafer. Four devices, one from each batch, have been singled out for RF measurement. All these bolometers are integrated with log periodic spiral antenna (Figure 1 and 2). Table 3 summarizes the room temperature resistance and the critical current of these devices.

Device ID	Film ID	Room Temp. Resistance (Ω)	Sheet Resistance (Ω/□)	Critical Current (μA)
CCN8-1E	CCN8-11	310	1550	430
NbTiN1/1-5	CCN8-1	150	750	240
NbTiN2/1-9	CCN8-5	140	700	465
NbTiN3/2-17	CCN8-15	170	850	243

Table 3: NbTiN films

3 Noise measurement

The noise measurement setup is shown in Figure 3. The mixer chip is attached to the backside of a 12 mm diameter elliptical silicon lens, which is mounted on the cold plate of a liquid He cryostat (18 inch Infrared Lab^{TM}). The lens is coated with 28 μm Parylene, which acts as an anti-reflection coating optimized at 1.6 THz. Radiation comes through a 1.2 mm thick high-density polyethylene window. A 0.25 mm Zitex^{TM} G108 filter is placed on the 4 K shield of the cryostat to block infrared radiation from entering the mixer. The local oscillator (LO) source for 0.7, 1.6 and 2.6 THz is a far infrared (FIR) laser. The LO and the RF beams are combined by a 12 μm thick Mylar beam splitter. The IF chain consists of an isolator and a 1.5-4 GHz low noise HEMT amplifier, which at 15 K temperature has about 2 K noise temperature in 2-4 GHz band and 5 K at 1.5 GHz. The IF signal is further amplified using two Miteq^{TM} room temperature amplifiers and measured through a YIG-filter (30 MHz bandwidth) and a microwave power meter.

Figure 4 Shows the measured IV curves of device NbTiN2/1-9 as an example. Figure 5 has a closer look at the IV curve around the optimum operating point. The lowest receiver noise temperature was achieved at rather large area which was between 0.8-2.2 mV bias voltage and 40-56 μA bias current. This is due to the rather large length of the these devices (0.7 μm compared to 0.4 μm long NbN devices).

The so called Y-factor technique is used to determine the receiver noise temperature. Y is the ratio between the receiver output power when hot (room temperature 295 K) and cold (liquid Nitrogen temperature 77 K) black bodies are used as signal sources. The receiver noise temperature is calculated as:

$$T_{rec} = \frac{T_{CW}(295) - Y T_{CW}(77)}{Y - 1} \tag{1}$$

Here $T_{CW}(T)$ is the equivalent temperature of a black body at temperature T defined as [20]:

$$T_{CW}(T) = T \left[\frac{hf/k_B T}{e^{hf/k_B T} - 1} \right] - \frac{hf}{2k_B} \tag{2}$$

where h is the Planck constant, k_B is the Boltzmann constant, f is the RF frequency and T is the physical temperature.

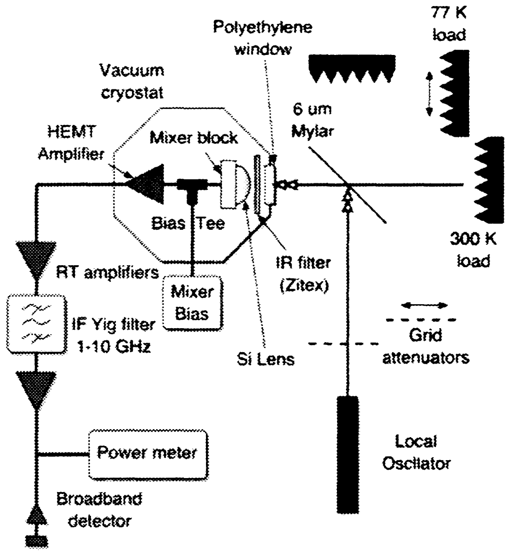

Figure 3: Noise measurement setup

Figure 6 shows the measured receiver noise temperature at 1.6 THz LO frequency versus IF frequency for all NbTiN mixers, mentioned above. As a comparison, a NbN mixer performance is also plotted. As one can see the NbTiN receiver noise temperature is almost the same as for NbN mixers at low IF frequency but the noise bandwidth is much smaller. Device (NbTiN3/2-17) was also measured at 0.7 and 2.6 THz LO frequencies (See Figure 7).

In our investigation we have used NbTiN films on AlN buffer layer (see §2). Gain bandwidth of NbTiN mixers on MgO buffer layer is discussed in [18]. The use of buffer layers for both NbTiN and NbN thin films has been reported in different papers. The superconducting critical temperature, transition width, normal state resistivity are observed to improve in these cases, compared to the films on bare substrates (Si, MgO, Quarts) [21, 22]. In HEB technology, T_c of superconducting films is not of that importance as for SIS mixers [23, 4]. Nevertheless, for ultra-thin films, where T_c is considerably lower than that for thick films or bulk material, a rise of 1-2 K for T_c can be quite important, since otherwise, it may not be possible to operate the mixers at 4.2 K (LHe) or 2 K (pumped LHe) temperature. Often, especially when substrate heating during film deposition is not available (or limited), the use of a buffer layer is the only way to obtain thin superconducting films with T_c above LHe temperature. There has been no report on NbTiN mixers without buffer layers. This is not the case for NbN HEB mixers. NbN HEB mixers with MgO buffer layers on both silicon and quarts substrates have been reported in [21, 22]. In both cases a deposition on 850 °C heated substrates was used. On quartz, the buffer layer results in an increase of the gain bandwidth by about 40 % (increase from 1.8 GHz to 2.5 GHz), while for silicon

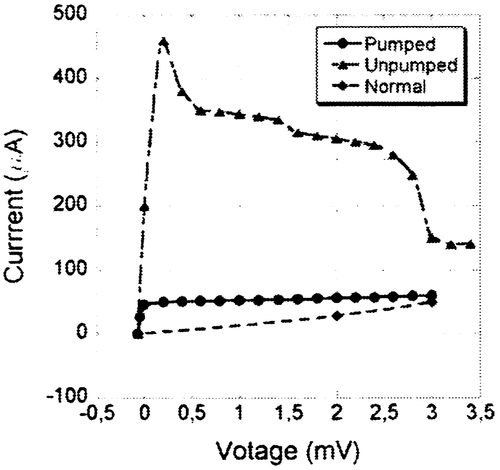

Figure 4: Unpumped, pumped and normal state IV curves of device No. NbTiN2/1-9.

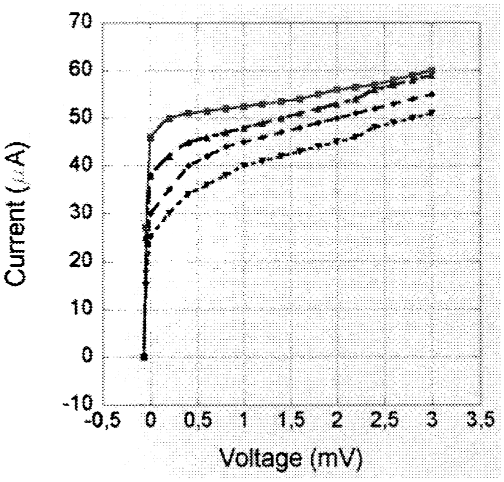

Figure 5: Pumped IV curves of device No. NbTiN2/1-9 around oprimum operating point.

the gain bandwidth change is less (3.5-4 GHz to 4.7 GHz) and becomes comparable for NbN HEBs on bare MgO substrate. Earlier experiments have demonstrated that for 3-4 nm NbN films the electron temperature relaxation time (40 ps) is limited by the phonon escape time [2], while the electron-phonon interaction time is much less (10 ps at 10 K [24]). Similar investigation for NbTiN films has clearly shown that for thin NbTiN films on MgO buffer layer (silicon substrate) the phonon escape time remains a bottle-neck of the electron relaxation rate for temperatures above 10 K [18]. In NbN the electron-phonon interaction time is inversely proportional to electron temperature (i.e. $\tau_{e\rightarrow p} \propto {T_e}^{-1.6}$ [24]). So far, direct measurements of the electron-phonon time in NbTiN thin films has not been done.

In this paper we present noise bandwidth measurements of NbTiN HEB mixers. As it has been shown [25], the noise bandwidth for HEB mixers is larger than the gain bandwidth. The receiver output noise temperature is a sum of the Johnson noise, T_J (proportional to the electron temperature, and therefore to T_c), thermal fluctuation noise, $T_{FL}(f) = T_{FL}(0)/(1+(f/f_0)^2$ (proportional to the ${T_c}^n$, where n is close to 2, depending on the HEB model used [26, 27]), and IF amplifier input noise T_{IF}. Here, f and f_0 are the IF and the 3 dB gain roll-off frequencies, respectively.

$$T_{out}(f) = T_J + T_{FL}(f) + T_{IF} = T_J + \frac{T_{FL}(0)}{1+(f/f_0)^2} + T_{IF} \qquad (3)$$

The DSB receiver noise temperature (referred to the receiver input) is:

$$T_{rec}(f) = \frac{T_{out}(f)}{2G(f)} \qquad (4)$$

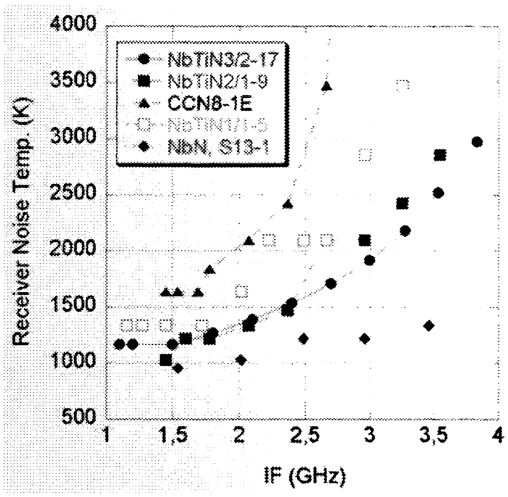

Figure 6: Measured receiver noise temperature vs. IF frequency at 1.6 THz LO frequency

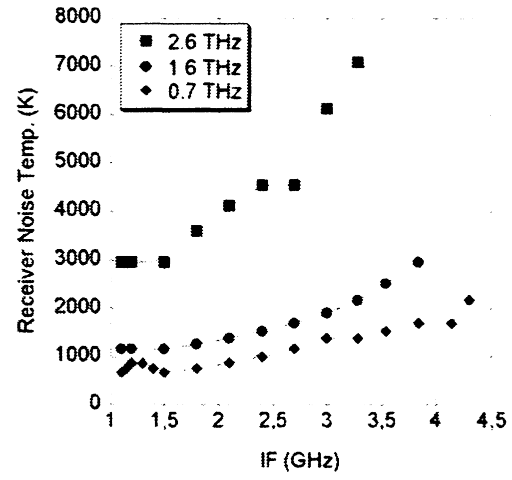

Figure 7: Measured receiver noise temperature vs. IF frequency at different LO frequencies using NbTiN3/2-17

where $G(f)$ is the SSB conversion gain. Since the gain dependence on the IF has a single pole Lorentzian shape, i.e. $G(f) = G(0)/(1 + (f/f_0)^2)$. then T_{rec} as a function of IF becomes:

$$T_{rec}(f) = T_{rec}(0) + \frac{(T_J + T_{IF})(f/f_0)2}{2G(0)} \tag{5}$$

Finally, if the noise bandwidth f_N is defined as the IF where $T_{rec}(f_N) = 2\ T_{rec}(0)$, then:

$$\frac{f_N}{f_0} = \sqrt{\frac{T_{out}(0)}{T_J + T_{IF}}} \tag{6}$$

The ratio between receiver output noise when mixer is in the superconducting state ($2T_{IF}$ is seen at the output) and in the operation point ($T_{out}(0)$ is seen at the output) is about 10 dB. From this together with the Y-factor measurement data, one can estimate that $T_{out}(0)$ is about 40 K. With $T_{out}(0) \approx 40$ K, $T_J \approx T_c = 8 - 9$ K and $T_{IF} \approx 2$ K, Equation (6) gives $f_N/f_0 \approx 2.2$. Experimentally, we obtained f_N to be 3-4 GHz for 0.7-2.6 THz LO frequency (see Fig 7). The reduction of HEB receiver noise bandwidth with LO frequency has been reported for NbN HEB mixers [28]. Taking the 2.5 GHz measured f_0 reported in [17], f_N/f_0 turns out to be about 1.2-1.6. Much smaller gain bandwidth for NbTiN HEB mixers on MgO buffer layer, 0.8 GHz at the optimal noise temperature bias point, was reported in [18]. Due to the observed dependence of the HEB mixers gain bandwidth on the deposition parameters and uncertainty of the film thickness (direct thickness measurements of the films 3-6 nm thick are very difficult), it becomes clear that to draw a conclusion about the gain-to-noise bandwidth ratio for the NbTiN HEB mixers reported in this paper. independent gain bandwidth measurements are needed.

4 Summary and Conclusions

Four batches of NbTiN HEB devices have been fabricated based on 4-7 nm thick NbTiN film deposited on 20 nm AlN buffer layer on heated high resistive Si substrate. showing good reproducibility of the fabrication technique. The receiver noise temperature was measured 700, 1100 and 3000 K at 0.7, 1.6 and 2.6 THz LO frequencies respectively at 1.5 GHz IF using a NbTiN HEB mixer integrated with a broadband spiral antenna. The measured noise bandwidth was about 3-4 GHz. This results show that the noise of these NbTiN mixers are already comparable with our NbN mixers at low IF frequencies. However the IF bandwidth of NbN mixers is about 5-6 GHz. which is considerably higher than for NbTiN. One possible reasons for this difference is the thickness of the NbTiN film, which is about 4-5 nm compared to 3.5 nm for NbN. The thickness of the film is one of the key parameters, which determines the temperature relaxation time of the hot electrons in the bolometer and consequently the IF bandwidth [29]. The process for deposition of high quality (high critical temperature and low sheet resistance) and thinner (3-4 nm) NbTiN films has to be developed to improve the IF bandwidth. Nevertheless, comparison of the published data shows that AlN buffer layer results in larger gain bandwidth, that indicates better acoustic matching of NbTiN films to AlN than to MgO.

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