Development of Phonon-Cooled NbTiN HEB Heterodyne Mixers for GREAT

S. Bedorf, P. Muñoz, T. Tils, C. E. Honingh and K. Jacobs

***Abstract*—The current development status of Niobium-Titanium Nitride (NbTiN) HEB mixers, for example for the GREAT receiver on SOFIA, is presented for both waveguide and quasi-optical mixers for 0.8, 1.9 and 2.7 THz LO frequency. For the waveguide mixers at 0.8 and 1.9 THz the HEBs are made on 2μm thick silicon nitride membranes which are suspended in a substrate channel perpendicular to the waveguide.**

For the quasi-optical mixer at 2.7 THz the devices are fabricated on Si-substrates and are integrated into spiral- and double-slot antennas and used with an extended hemispherical silicon lens. Our measurements show that the waveguide/membrane mixers work well at both 800 GHz and 1.9 THz.

To increase the required IF bandwidth we are developing thin NbN films. The first results of the NbN thin film development are presented in the paper.

I. Introduction

CURRENTLY, state-of-the-art phonon-cooled HEBs are usually made of Niobium Nitride (NbN) thin films, but results at 800 GHz [1] and above 1 THz [2] have shown that Niobium Titanium Nitride (NbTiN) can be used as well. The physical and chemical properties of NbTiN and NbN thin films are closely related and quite similar. Recently it was shown experimentally that the response of a phonon-cooled HEB depends strongly on the nature of the contact from the active superconductor to the Au-leads. By cleaning this interface and by inserting a thin superconducting layer, an increase in IF bandwidth and a reduced level of LO power was observed in [3].

We have investigated the influence of different clean processes and contact pad materials on the DC characteristics of NbTiN HEBs. Also, we present RF measurements of devices which have been fabricated using this approach.

Two types of mixer designs are presented in this work, a quasi-optical mixer based on an extended hemispherical silicon lens integrated with a logarithmic spiral antenna and a waveguide mixer based on 2 μm thick silicon nitride membranes which are suspended in a substrate channel.

II. Device Fabrication

Both kinds of mixers are based on 4-5 nm thin NbTiN films which are deposited on high resistivity silicon substrates for the quasi-optical design and a Si_3N_4 membranes for the waveguide design by DC reactive magnetron sputtering using a $Nb_{78\%}Ti_{22\%}$ alloy sputtering-target in a mixture of Ar and N_2.

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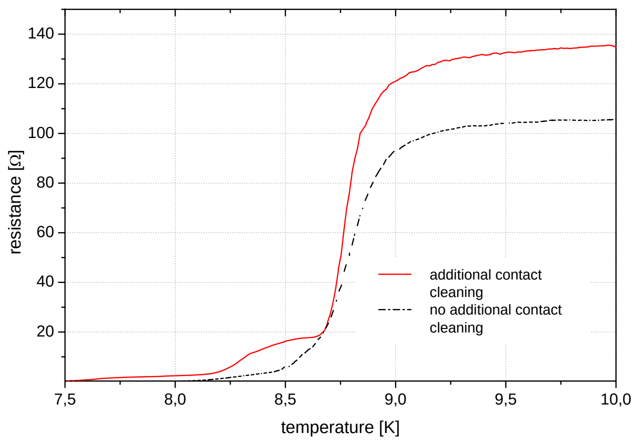

Fig. 1. Resistance versus temperature curves of two devices with and without additional cleaning of the interface area.

The substrate is heated to 600°C during deposition. The deposition process is optimized to yield a critical temperature T_c of 8-8.5 K for 4-5 nm films. The film has a normal-state resistance of approximately 300 Ω per square. The active area of the HEB is defined by electron beam lithography to form a microbridge about 0.4 μm long and 2 μm wide.

The nature of the contacts determines the interface transparency between the bolometer and the contact structure. Cleaning the interface leads to a better control over the interface.

The cleaning process consists of an oxygen plasma etching step, followed by an argon physical plasma etching step. To restore the superconducting film properties that might be affected by the cleaning process, a NbTiN layer (10 nm) is deposited on top of the contact area. The result is shown in the resistance versus temperature (RT) curve in Figure 1.

Two different superconducting transitions are observed, one due to the NbTiN bridge itself and the lower transition due to the interface between the pads and the NbTiN bridge. [4]. The parts of the bridge close to the contact pads show a reduction of the critical temperature T_c associated with a superconducting proximity effect, which is influenced by the interface transparency. Devices with additional cleaning show a larger resistance at the lower transition. A higher value of the resistance at the lower transition is caused by a larger proximity effect and therefore indicates a better interface transparency. A better interface transparency gives less RF losses and could improve the HEB sensitivity and LO requirement. This is indeed observed for NbN HEB devices.

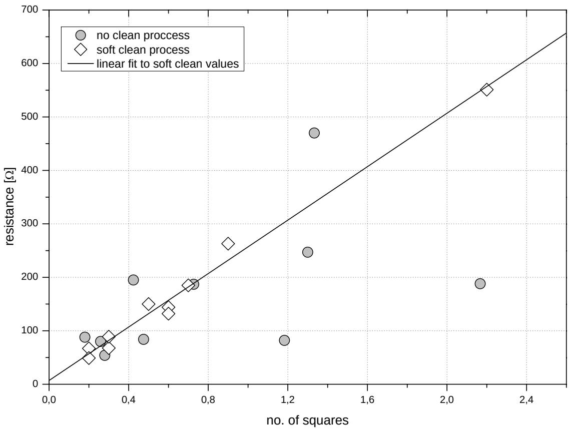

Fig. 2. Resistance versus nominal bridge dimension (in number of squares) for devices with and without additional cleaning

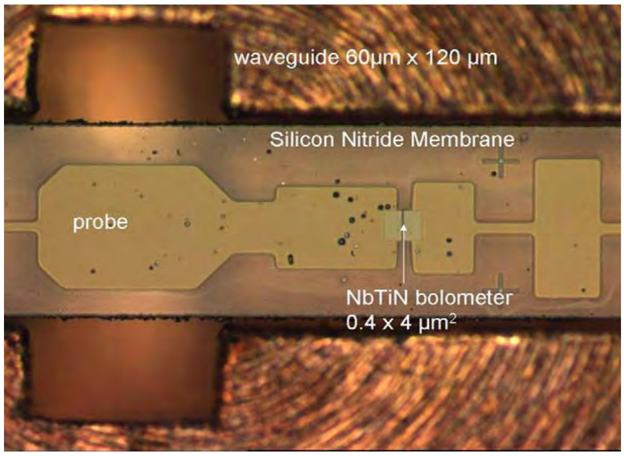

Fig. 3. 1.9 THz bolometer mixer with 0.4 x 4 μm NbTiN HEB device. The horn antenna is removed and the device metallization is seen through the backside of the transparent 2 μ SiN membrane

HEB devices with different lengths have been fabricated to investigate more precisely the influence of cleaning the interface. Figure 2 shows the nominal bridge dimension in number of squares versus the resistance for HEB devices with and without additional cleaning. The dashed line is a linear fit to the resistance values for the devices with additional cleaning. Devices with additional cleaning show very little deviation from the linear behavior, while devices without additional cleaning show a significant deviation from the linear scaling which is attributed to an uncontrolled contact resistance. The contact resistance for HEB devices with additional cleaning is 7 Ω, indicated by the y-axis intercept of the linear fit. Devices with an additional cleaning of the interface show a much better reproducibility in the values of the normal state resistance.

III. RF Measurements

All devices used for the RF measurements are devices with an additional cleaning of the interface as described above. For the waveguide mixer, the membrane with the HEB is flip-chip bonded to a silicon frame. This frame is subsequently mounted in a standard fixed tuned waveguide mixer block. Figure 3 shows the inner part of the waveguide 1.9 THz HEB mixer.

For the quasi-optical mixer the substrate with the HEB device is clamped onto the flat side of an extended hemispherical silicon lens.

The noise performance of the mixers was measured at 800 GHz. The uncorrected receiver noise T_{rec} as a function of the intermediate frequency (IF) is measured using the standard Y-factor method. The local oscillator (LO) source for 800 GHz is a solid state LO with an output power of max. 30 μW. The signal and the LO radiation are superimposed by a 50 μm Mylar beamsplitter (44% reflection) for the quasi-optical mixer and 13 μm (8.8% reflection) Mylar beamsplitter for the waveguide mixer.

The lowest measured DSB receiver noise-temperature is T_{rec} = 650 K for waveguide mixer. The quasi-optical mixer shows a higher receiver noise temperature of T_{rec} = 3000 K at 800 GHz. Figure 4 shows the measured receiver noise

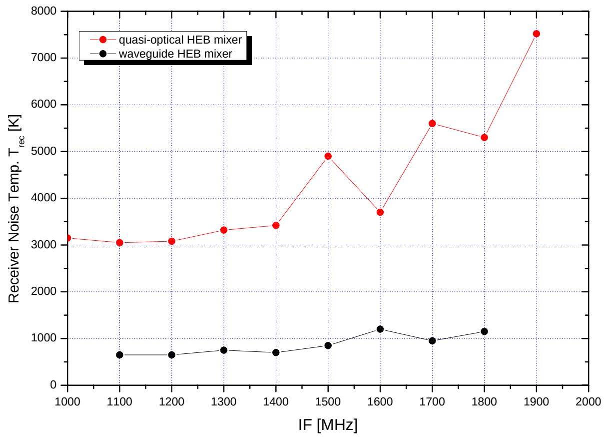

Fig. 4. Noise temperature versus IF at 800 GHz for waveguide and quasi-optical NbTiN HEB mixer

temperature at 800 GHz LO frequency versus IF frequency for both mixer types. The device size of HEB used for the quasi-optical is 2.8 x 0.5 μm and 4.5 x 0.35 μm for the waveguide mixer. The noise bandwidth is found to be approximately 1.5 GHz for both mixers. As the devices are very similar, the reason for the decreased sensitivity is a yet unknown coupling loss.

We have used a Fourier Transform Spectrometer (FTS) to measure the spectral response of the 1.9 THz waveguide mixer. In figure 5 the FTS measurement is shown and compared to simulated data. The simulation is done in CST Microwave Studio [5]. From the calculated impedance versus frequency the coupling factor is obtained by matching the impedance data to the normal state resistance of this specific device, in this case 34 Ω.

For the measurement the optical path is evacuated to approx. 1 mbar. The measured bandwidth is smaller than the predicted one. The drop of the coupling factor at 1.6 THz is probably a feature of the measurement setup. The simulated bandpass correspond fairly well to the measurement.

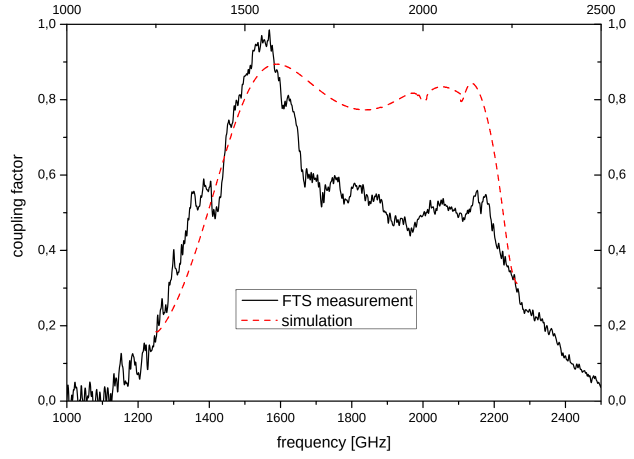

Fig. 5. Spectral response of the 1.9 THz waveguide HEB mixer measured by FTS in direct detection mode as function of frequency. The dashed line indicates the simulation.

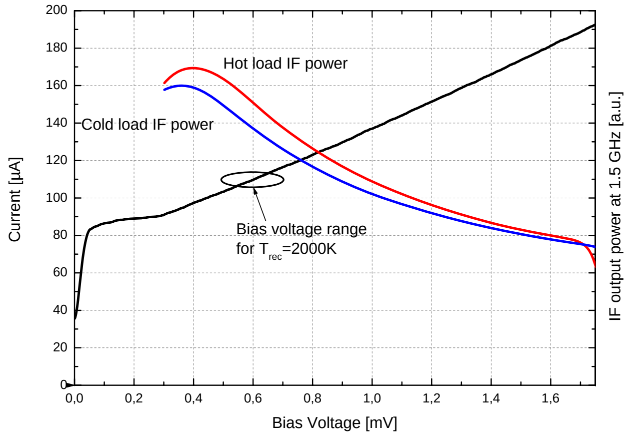

Fig. 6. Current-voltage (IV) curve of the 1.9 THz NbTiN waveguide HEB mixer with LO power at 1.75 THz. The HEB device size is 0.4 x 4 μm. Also shown is the IF output power in response to hot (295K) and cold (77K) loads placed at the receiver input.

First experiments of a 1.9 THz waveguide HEB mixer were performed at 1.75 THz using a FIR laser as LO source. The CO_2 laser is tuned on a 9P36 line and pumps the methanol line at 170.57 μm wavelength. The current-voltage (IV) characteristic of the 0.4 x 4 μm device with LO power at 1.75 THz is shown in Figure 6. Also shown in Figure 6 is the receiver output in response to hot and cold loads. The optimal sensitivity is achieved at a bias voltage of 0.5 - 0.7 mV and a bias current of roughly 110 μA. The uncorrected measured noise temperature at this bias point is about 2000 K. A beam splitter with 29% reflection loss was used which adds substantially to the mixer noise.

For the GREAT receiver the 1.9 THz waveguide mixer will be pumped using a BWO with a frequency tripler as LO. The estimated LO power of the BWO with the frequency tripler is max. 2.4 μW. A Martin-Puplett-Interferometer was used to superimpose the LO and the signal radiation. Figure 7 shows the current-voltage characteristics of the 1.9 THz waveguide HEB mixer with and without LO power. This is our first time to pump the 1.9 THz waveguide mixer using a BWO with a frequency tripler. Form Figure 7 we see that it is possible to pump the device almost to normal state resistance, demonstrating the possibility to use the BWO with frequency tripler as LO source for the GREAT receiver.

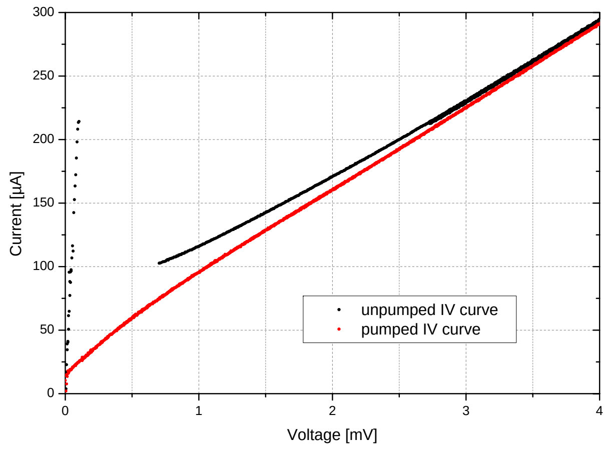

Fig. 7. The I-V curves of the 1.9 THz waveguide HEB mixer with and without LO power at 1.9 THz using a BWO with a frequency tripler.

IV. NbN HEB mixers

The NbTiN HEBs fabricated for GREAT show a rather limited noise bandwidth of about 1.5 GHz. The HEB devices fabricated on thin Si_3N_4 membranes do not show a different IF noise bandwidth than the devices fabricated on much thicker Si wafers. That indicates that the cooling mechanism to the substrate of the waveguide mixer is not the limiting factor for the IF bandwidth of these mixers. An experiment in collaboration with Delft University of Technology, Physics of NanoElectronics (R. Barends) indicated an intrinsically slower electron-phonon τ_{e-ph} interaction for NbTiN compared to NbN. Even though the actual IF bandwidth of the NbTiN HEB devices could only be measured with an appropriate IF system, the results of this work show that NbTiN is potentially inferior in bandwidth to NbN. To increase the IF bandwidth for the GREAT HEB mixers, 3-4 nm thin NbN films, fabricated at KOSMA, will be used for the next generation of our HEB mixers.

The thin NbN films are deposited onto 350 μm high resistivity Si substrates. The NbN films are deposited by DC magnetron sputtering in a Ar/N_2 atmosphere. For the thin films a low sputtering rate of 2-5 Å/s is desired. Therefore, a small constant current of 0.3 A is used.

Figure 8 shows the resistance versus temperature (RT) curves for 4 and 5 nm thin NbN films on high-resistivity Si. The 4 nm thin films which will be used for the HEB device fabrication have a critical temperature T_c = 8.7 K and a transition width of ΔT_c = 1.7 K. The surface resistance of the 4 nm thin films is about 800 Ω. The deposition rate is 2 Å per second.

To deposit 4 nm thin NbN films with these characteristics, substrate heating is essential. Substrate heating is achieved by using a PBN/Pyrolytic (PG) resistance heating element with an operating temperature up to 1800°C.

The influence of heating the substrate during deposition on the superconducting properties of 5 nm thin NbN films is shown in Figure 9. Heating the substrate up to 600°C significantly increases the critical temperature T_c from 8.1 K at ambient temperature to 9.4 K. The transition width ΔT_c becomes slightly smaller.

In order to verify the uniformity of the critical temperature T_c across the wafer, a 30 x 30 mm wafer was cut into three 10 x 30 mm pieces after the deposition. The critical temperature was measured at distances of 5 mm across the wafer slice to get an indication of the large-scale critical temperature distribution across the wafer. Figure 10 shows the resistance versus temperature diagram of the 5 different position on the center part of a split wafer. The NbN film is about 4 nm thick. The identifiers A2-A6 and B6-B7 indicate contact positions on the wafer in 5 mm distance, respectively. Although the critical temperature T_c of the wafer is lower than the expected T_c for a 4 nm thin NbN film, figure 10 clearly shows that the critical temperature and the resistance ratio R_{300}/R_{20} remains constant, indicating that the film thickness is very uniform across the 10 x 30 mm wafer. The resistance in this diagram varies because the four-point probe distance was different for each measurement point.

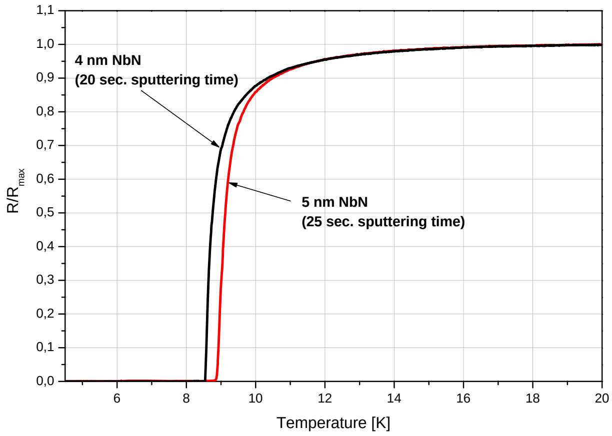

Fig. 8. Resistance versus temperature curves of 4 and 5 nm thin NbN films on high-resistivity Si.

V. Conclusion

We have demonstrated receiver noise temperature of 650 K and 3000 K at 800 GHz for waveguide on suspended Si_3N_4 membrane and quasi-optical mixers respectively. The IF noise bandwidth is 1.5 GHz for both mixers. The comparable IF-bandwidth for Si and Si_3N_4 substrates indicates that the present IF bandwidth is dominated by intrinsic NbTiN film parameters. The additional cleaning of the interface did not improve the noise temperature or the IF bandwidth compared to previous HEB batches fabricated without additional cleaning. Cleaning the interface area however shows a much better reproducibility of the normal state resistance.

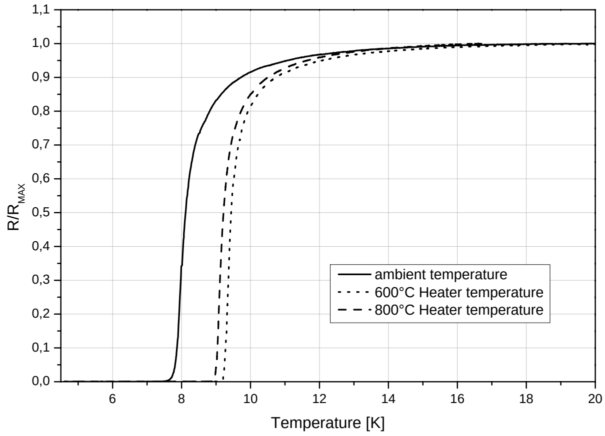

Fig. 9. R(T) curves for 5 nm ultrathin NbN films on Si-substrates for different temperatures during deposition.

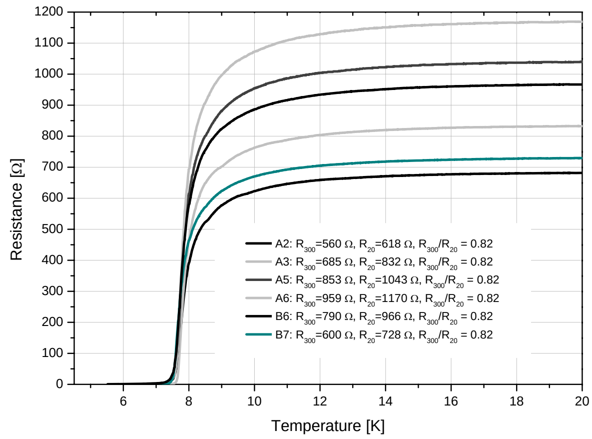

Fig. 10. Resistance versus temperature of a 4 nm thin NbN film measured across a 10 x 30 mm large wafer. The identifier A2-A6 and B6-B7 are contact positions on the wafer in 5 mm distance respectively.

The first heterodyne measurements of the 1.9 THz waveguide GREAT HEB receiver based on NbTiN showed an uncorrected receiver noise temperature of $T_{rec} \approx 2000$ K using a FIR laser as LO source. It is also possible to pump the 1.9 THz HEB mixer using a BWO with a frequency tripler. Receiver noise temperature measurements using the BWO will follow.

To increase the required IF bandwidth of the GREAT HEB mixers we are developing thin NbN films. The first results of 4 nm thin NbN films on high-resistivity Si show a critical temperature of T_c = 8.7 K and a sheet resistance of $R_{\square} \approx$ 800 Ω. The large-scale critical temperature distribution is very uniform across the wafer. The next batch of our HEB devices will be fabricated based on 4 nm thin NbN on Si and Si_3N_4.

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