# Improved sensitivity of NbN hot electron bolometer mixers by vacuum baking

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Abstract—We find that the sensitivity of heterodyne receivers based on superconducting hot-electron bolometer (HEB) increases by 25 – 30% after baking at 85 °C and in a high vacuum. The devices studied are twin-slot antenna coupled HEB mixers with a small NbN bridge of  $1 \times 0.15 \ \mu m^2$ . The mixer noise temperature, gain, and resistance versus temperature curve of a HEB before and after baking are compared and analyzed. We show that baking reduces the intrinsic noise of the mixer by 37 % and makes the superconducting transition of the bridge and the contacts sharper. We argue that the reduction of the noise is due to the improvement of the transparency of the contact/film interface. The lowest receiver noise temperature of 700 K is measured at a local oscillator frequency of 1.63 THz and a bath temperature of 4.3 K.

#### I. INTRODUCTION

In recent years phonon-cooled hot electron bolometer (HEB) mixers have matured as the only sensitive heterodyne detector for the frequency range from 1.5 to 6 THz [1], [2], [3], [4]. HEBs based on thin superconducting NbN film with a fast electron-phonon cooling are particularly attractive due to their high sensitivity and large intermediate frequency (IF) bandwidth. Theoretically it has been predicted that such mixers could have nearly quantum noise limited sensitivity [5]. However, the best double sideband (DSB) receiver noise temperature  $(T_{rec,DSB})$  reported so far is 950 K at 2.5 THz, corresponding to 8  $h\nu/k_b$ , where h is Plank's constant,  $\nu$  the frequency, and  $k_b$  Boltzmann's constant. This result was achieved in a spiral-antenna coupled large NbN HEB (4×0.4  $\mu$ m<sup>2</sup>) mixer by cleaning the surface of the NbN film and depositing a superconducting NbTiN interlayer and a standard Au layer as the contacts during fabrication [4], [6]. By applying the same contacts, a  $T_{rec,DSB}$  of 900 K has been obtained in a twin slot antenna coupled small NbN HEB  $(1 \times 0.15 \ \mu m^2)$  mixer at 1.6 THz [7]. Despite of the fact that similar result has been reproduced in devices fabricated in other runs, fluctuations in the sensitivity have been observed among a large number of batches. We report here that the sensitivity of "poor" NbN HEB mixers can be improved by vacuum baking. To understand the result, we monitor and analyze the dc properties, the mixer noise temperature, and the mixer conversion gain before and after baking.

#### II. EXPERIMENTAL

The NbN HEB mixers studied in the present work are fabricated using a standard thin NbN film (with an intended thickness of 3.5 nm) on a Si substrate with a superconducting transition temperature  $T_c$  of 9.5 K, and coupled by a twinslot antenna designed for 1.6 THz (see the inset of Fig. 1). The superconducting bridge of the mixer is 1  $\mu$ m wide and 0.15  $\mu$ m long and the contacts are made of Au/NbTiN. Before deposition of the contact layers, a short  $O_2$  plasma etch is first applied to remove resist remnants and then a short insitu Ar sputter etch is introduced to clean the film surface. We anticipate this to be a critical step technologically, which can result in the fluctuations of the interface quality from batch to batch. The fabrication process is very similar to our early work [6], except for the definition of the antenna and a passivation layer. The passivation  $SiO_2$  layer of 500 nm is sputtered on top of the active region of the HEB mixer, to prevent the aging effect in normal lab conditions. Although several devices were measured, we focus here on the one showing a normal state resistance  $(R_N)$  of 153  $\Omega$  at 16 K and a slightly reduced  $T_c$  of around 9 K. Vacuum baking has been performed in an oven connected to a turbo pump. Before switching on and setting it to 85°C, the oven has been pumped for 24 hours and the pressure reached  $10^{-5}$  mbar. Under these conditions the devices were baked for 72 hours.

We measure the receiver noise temperature, the gain, and the dc resistance versus temperature (RT) curve before and after baking. We use a RF (radio frequency) test setup for a typical Y-factor measurement. A standard quasi-optical technique is applied to couple RF signal from the free space to the HEB. The HEB chip is glued on the backside of an elliptical silicon lens. The lens is placed in a metal mixer block, thermally attached to the 4.2 K cold plate of a vacuum cryostat. Blackbody signal sources (Eccosorb) are used as the signal, which defines a hot load at 295 K and a cold load at 77 K. The signal is combined with the local oscillator (LO) signal via a 3.5  $\mu$ m thick Mylar beam splitter. Both of the signals transmit further into the lens though a 1.1 mm thick HDPE window (RF loss of -1.1 dB) and a Zitex G104 (-0.45 dB) heat filter at 77 K. The LO source is an optically pumped gas laser at 1.63 THz and is attenuated with a rotatable grid. The IF signal



Fig. 1. Current-voltage characteristics of a NbN HEB mixer without and with LO power, before baking. In the inset: a) a cross-section view of the bridge and the contacts of the HEB mixer; b) a top view of the HEB mixer before the deposition of the  $SiO_2$  layer, where the bridge, antenna, and RF filter structure are indicated. The transmission line (not indicated) connects the HEB to the antenna.

is amplified by a low noise amplifier with 40 dB gain and a noise temperature of 5 K. The signal is further amplified by a room temperature amplifier with 41 dB gain and is filtered in a 80 MHz bandwidth at 1.4 GHz before detection with a power meter. The Y-factor used for calculating the receiver noise temperature, is the ratio of the measured IF output powers responding to the hot and cold loads [8]. The dc resistance is measured using a standard lock-in technique.

#### **III. RESULTS AND DISCUSSION**

## A. Current-voltage characteristics

In Fig. 1 we plot the current-voltage (IV) curves without and with applying LO power before the device is baked. We measured also the unpumped and pumped IV curves after baking and find a small reduction of the critical current from 68  $\mu A$  to 65  $\mu A$  and a small (4  $\Omega$ ) increase of  $R_N$ . However, the pumped IV curves are similar. In particular, the optimal IV curve, where the lowest noise temperature is obtained, remains unchanged. Based on the IV curves at different pumping levels, the LO power absorbed by the HEB is estimated using the isothermal technique [9]. The optimal LO pumping level is around 50 nW for both cases.

# B. DSB receiver noise temperature

The  $T_{rec,DSB}$  calculated according to the Callen-Welton definition [8] are plotted in Fig. 2 as a function of bias voltage at the optimal LO power before and after baking. Note that in both cases an uncoated Si lens is used and the total RF loss in the signal path is -4.35 dB. As indicated in the figure, the  $T_{rec,DSB}$  after baking decreases significantly over the whole voltage bias range. At the optimal bias point (0.6 mV), the  $T_{rec,DSB}$  decreases by 27% and becomes 1050 K, which is slightly lower (7%) than the previous best result for the case of the uncoated lens [7]. Similar improvement was observed in four other devices, showing a decrease of 25 – 30% in  $T_{rec,DSB}$ .



Fig. 2. Receiver noise temperature (DSB) of the HEB mixer as a function of bias voltage obtained before and after baking. Symbol notation: open squares and up-triangles - before and after baking measured on an uncoated lens; closed up-triangles - after baking measured using a coated lens and a cold bandpass filter.



Fig. 3. Mixer noise temperature (SSB) and conversion gain (SSB) of the HEB mixer as a function of bias voltage. The open squares denote the value before baking; the open up-triangles - after baking.

#### C. SSB mixer noise temperature and conversion gain

 $T_{rec,DSB}$  reflects the effective noise temperature of a cascade of the optics (all of the optical components and the transmission efficiency of the atmosphere), mixer, and IF amplifier. After subtracting the contributions from the optics and IF amplifier, we derive the single sideband (SSB) mixer noise temperature  $T_{mixer,SSB}$  and the SSB mixer conversion gain  $G_{mixer,SSB}$ , which are plotted as a function of bias voltage in Fig. 3. We observe that, after baking the mixer gain changes rather small. Around the optimal bias point, it increases less than 13%. The mixer noise temperature  $T_{mixer,SSB}$  decreases by 44%. The lowest  $T_{mixer,SSB}$  found is 590 K. Since the output noise of a HEB equals to  $T_{mixer} \times G_{mixer}$ , the baking in essence reduces the intrinsic noise by 37%.

#### D. Device resistance versus temperature curve

We assume that the coupling of the RF signal via the antenna and transmission line into the HEB remains unchanged after baking. This is supported by the gain data and by the measured direct response of the HEB by Fourier Transform Spectroscopy, which shows essentially the same spectrum after baking. To understand the reduction of the noise, we need to look closely at the changes of the HEB itself. For this reason, we measured its RT characteristics before and after baking. The result is given in Fig. 4, together with the derivative of resistance dR/dT (in the inset). We observe three superconducting transition features in the RT curve and define  $T_c$  (the highest) for the bridge,  $T_{c1}$  (the middle) for the contact pads, and  $T_{c2}$  (the lowest) for the transmission line/RF filter structure according to an early study [10]. These values in our case correspond to the peak positions in the dR/dT. As one can see, baking certainly affects the bridge, reducing the  $T_c$ and the transition width  $\Delta T_c$  as well. We determine the exact values using the broken line method [5] and list them in table I. The baking also makes also the superconducting transition in the RT curve at  $T_{c1}$  (the contacts) and  $T_{c2}$  (the transmission line/RF filter structure) considerably sharper, indicated clearly by both RT and dR/dT curves.

# E. Discussions

Before we attempt to associate the RT behaviour to the reduced noise, we briefly describe another baking experiment in similar HEBs, but from two good batches. These devices show good sensitivity as in [7] and relatively sharp RT curves as the one in Fig. 4 after baking. In this case, the baking gives either no effect or improves  $T_{rec}$  slightly. We notice that the RT ( $T_c$  and  $\Delta T_c$ ) of the bridge behaves in a very similar way as the one shown in Fig. 4, but not the transition associated to the contacts. The latter stays the same. Thus, we do not consider the change of RT in the bridge as a possible explanation. Instead, we ascribe the reduced noise to an improvement of the contact/film interface. The sharper transition in the contacts suggests a more homogeneous contact/film interface. This fact recalls the results of the previous work [4], [6], that different cleaning and contact structure can influence the performance of the mixer significantly.

To fully explain our result, one requires a theoretical model which is able to calculate the gain and noise by including the resistive transition, the contacts, and noise sources. Such a model is in progress [11], [12], [13], [14], but not fully applicable yet. An offshoot of our experiment is that we can prove that the lumped element model [5] based only on the superconduction transition of the bridge seems to be not applicable to our case. In this model, the mixer noise temperature is dominated by the thermal fluctuation noise  $T_{Mixer}^{TF}$ , which is given by  $T_{Mixer}^{TF} \propto T_c$ . The mixer gain is given by  $G_{Mixer} \propto T_c / \Delta T_c$ . Using the inputs from table I, after baking the  $T_{mixer}$  is expected to decrease by 3.5 %, while the  $G_{Mixer}$  should increase by 57 % (2.0 dB), which disagree the measured  $T_{mixer}$  (44 %) and the  $G_{Mixer}$  (13 % (0.6 dB)).

To determine the ultimate receiver noise temperature of the device after baking, we reduce the RF loss (1 dB) in the optics by applying a Si lens coated with an antireflection layer of 29  $\mu$ m thick Parylene C. In addition, we also add



Fig. 4. The resistance (R) of the HEB mixer as a function of temperature before (solid line) and after (dash-dotted line) baking.  $T_c$ ,  $T_{c1}$ , and  $T_{c2}$  correspond to the transition temperature of the bridge, the contact pads and the transmission line/the RF filter structure respectively (see Fig. 1). The inset shows the dR/dT as a function of temperature.

TABLE I Relevant parameters for the superconducting transition in the bridge before and after baking

Parameter	Before baking	After baking
$T_c[\mathbf{K}]$	8.68	8.37
$\Delta T_c[\mathbf{K}]$	1.55	0.95

a metal mesh RF bandpass filter with an effective bandwidth of 200 GHz centered at 1.6 THz, mounted on the 4.2 K cold plate, which filters the hot/cold load power and thus reduces the direct detection effect of broadband radiation [15]. This effect, which can reduce a Y-factor, is particularly important in the case of the small volume HEBs. The measured new receiver noise temperature is also plotted in Fig. 2. We observe that the receiver noise temperature further decreases, with the lowest  $T_{rec,DSB}$  of 740 K around the optimal operating point (0.4 mV). In this case the total optical loss is -3.87 dB. By flushing the signal path with dry  $N_2$  gas, which reduces loss of 0.3 dB due to the water absorption in the air, we measured a  $T_{rec,DSB}$  of 700 K (not shown in Fig. 2), corresponding to 9  $h\nu/k_b$ . This value is identical to the record sensitivity reported in a spiral-antenna coupled large (4×0.4  $\mu$ m<sup>2</sup>) HEB mixer at the same frequency [3], [16].

#### **IV. CONCLUSION**

In conclusion, we have demonstrated that baking can reduce the receiver noise temperature of NbN HEB mixers. The analysis shows that the baking reduces the intrinsic noise of the mixer by 37 %, but gives little effect on the mixer gain. Based on the RT before and after baking, we attribute the improvement in sensitivity to the role of the contact/NbN interface. The lowest measured receiver noise temperature is 700 K at 1.63 THz. The IF impedance and gain of the same device as a function of frequency have also been measured and are reported in a separated paper by Kooi *et al* [17].

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#### REFERENCES

- E.M. Gershenzon, G.N. Golt'sman, I.G. Gogidze, A.I. Eliantev, B.S. Karasik and A.D. Semenov, "Millimeter and submillimeter range mixer based on electron heating of superconducting films in the resistive state", *Sov. Phys. Superconductivity*, vol. 3, pp. 1582, 1990.
- [2] A.D. Semenov, H.-W. Hübers, J. Schubert, G.N. Golt'sman, A.I. Elantiev, B.M. Voronov, and E.M. Gershenzon, "Design and performance of the lattice-cooled hot-electron terahertz mixer", *J. Appl. Phys.*, vol. 88, no. 11, pp.6758-6767, 2000.
- [3] S. Cherednichenko, P. Khosropanah, E. Kollberg, M. Kroug, and H. Merkel, "Terahertz superconducting hot-electron bolometer mixers", *Physica C*, vol. 372-376, pp. 407-415, 2002.
- [4] J.J.A. Baselmans, M. Hajenius, J.R. Gao, T.M. Klapwijk, P.A.J. de Korte, B. Voronov and G. Gol'tsman., "Doubling of sensitivity and bandwidth in phonon cooled hot electron bolometer mixers", *Appl. Phys. Lett.*, vol. 84, pp. 1958-1960, 2004.
- [5] B.S. Karasik and I. Elantiev, "Noise temperature limit of a superconducting hot-electron bolometer mixer", *Appl. Phys. Lett.*, vol. 68, pp. 853-855, 1996.
- [6] M. Hajenius, J.J.A. Baselmans, J.R. Gao, T.M. Klapwijk, P.A.J. de Korte, B. Voronov and G. Gol'tsman., "Low noise NbN superconducting hot electron bolometer mixers at 1.9 and 2.5 THz", *Supercond. Sci. Technol.*, vol. 17, S224-228, 2004.
- [7] J.J.A. Baselmans, M. Hajenius, J.R. Gao, P.A.J. de Korte, T.M. Klapwijk, B. Voronov and G. Gol'tsman, "Doubling of sensitivity and bandwidth in phonon cooled hot electron bolometer mixers", *Proc. of the SPIE*, *vol. 5498: Millimeter and Submillimeter Detectors for Astronomy II*, by J. Zmuidzinas, W. S. Holland, S. Withington, Editors, 23-25 June 2004, Glasgow, Scotland, UK, p. 168-177.
- [8] A.R. Kerr, "Suggestions for Revised Definitions of Noise Quantities, Including Quantum Effects", *IEEE Trans. on Microwave Theory and Techn.*, vol. 47, no. 3, pp. 325-329, 1999.
- [9] H. Ekström, B.S. Karasik, E.L. Kollberg, and K.S. Yngvesson, "Conversion gain and noise of niobium superconducting hot-electron mixers", *IEEE Trans on Microwave Theory and Tech.*, vol. 43, pp. 938-947, 1995.
- [10] M. Hajenius, R. Barends, J.R. Gao, T.M. Klapwijk, J.J.A.Baselmans, A. Baryshev, B. Voronov and G. Gol'tsman. "Local resistivity and the current-voltage characteristics of Hot Electron Bolometer mixers", *IEEE Trans. on Appl. Super.*, in press, 2005.
- [11] D. Wilms Floet, E. Miedema, T.M. Klapwijk, and J.R. Gao, "Hotspot mixing: A framework for heterodyne mixing in superconducting hotelectron bolometers", *Appl. Phys. Lett.*, vol. 74, pp. 433-435, 1999.
- [12] H. Merkel, P. Khosropanah, P. Yagoubov, and E. Kollberg,"A hot spot mixer model for superconducting phonon-cooled HEB far above the quasiparticle bandgap", *Proceedings of the 10<sup>th</sup> International Symposium Space Terahertz Technology*, Charlottesville, March 16-18, 1999, pp. 592-606.
- [13] T.M. Klapwijk, R. Barends, J.R. Gao, M. Hajenius, and J.J.A. Baselmans, "Improved superconducting hot-electron bolometer devices for the THz range", *Proc. of the SPIE, vol. 5498: Millimeter and Submillimeter Detectors for Astronomy II*, by J. Zmuidzinas, W. S. Holland, S. Withington, Editors, Glasgow, Scotland, UK, 23-25 June 2004, pp. 129-139.
- [14] R. Barends, M. Hajenius, J.R. Gao, and T.M. Klapwijk, "Direct correspondence between HEB current-voltage characteristics and the currentdependent resistive transition", *The 16th Int. Symp. on Space Terahertz Technology*, Göteborg, Sweden, 2-4 May 2005, (preprint).
- [15] J.J.A. Baselmans, A. Baryshev, S.F. Reker, M. Hajenius, J.R. Gao, T.M. Klapwijk, B. Voronov and G. Gol'tsman, "Direct detection effect in small volume hot electron bolometer mixers", *Appl. Phys. Lett.*, vol. 86, pp.163503-163505, 2005.
- [16] M. Kroug, S. Cherendnichenko, H. Merkel, E. Kollberg, B. Voronov, G. Gol'tsman, H.W. Hübers, H. Richter, "NbN hot electron bolometric mixers for terahertz receivers", *IEEE Trans. on Appl. Supercond.*, vol. 11, pp. 962-965, 2001.

[17] J. W. Kooi, J. J. A. Baselmans, J. R. Gao, P. Dieleman, Z. Q. Yang, A. Baryshev, M. Hajenius, G. de Lange, and T. M. Klapwijk, "IF Impedance and Mixer Gain of Phonon Cooled Hot-Electron Bolometers and the Perrin-Vanneste/Nebosis Two Temperature Model", *The 16th Int. Symp. on Space Terahertz Technology*, Göteborg, Sweden, 2-4 May 2005, (preprint).