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RAPID COMMUNICATION

# Reduced noise in NbN hot-electron bolometer mixers by annealing

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**Abstract**
We find that the sensitivity of heterodyne receivers based on superconducting hot-electron bolometers (HEBs) increases by 25–30% after annealing at 85 °C in vacuum. The devices studied are twin-slot antenna coupled mixers with a small NbN bridge of $1 \times 0.15\ \mu\mathrm{m}^2$. We show that annealing changes the device properties as reflected in sharper resistive transitions of the complete device, apparently reducing the device-related noise. 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.

In recent years phonon-cooled hot-electron bolometer (HEB) mixers have matured as the most sensitive heterodyne detector for the frequency range from 1.5 to 6 THz [1–4]. HEBs based on a 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 extremely low mixer noise temperature, determined by the sharpness of the transition of the superconductor and the critical temperature [5]. The best double sideband (DSB) receiver noise temperature ($T_{\mathrm{rec,DSB}}$) reported so far is 950 K at 2.5 THz, corresponding to 8 $h\nu/k_{\mathrm{b}}$, where $h$ is Plank's constant, $\nu$ the frequency, and $k_{\mathrm{b}}$ Boltzmann's constant. This result was achieved in a spiral-antenna coupled relatively large NbN HEB ($4 \times 0.4\ \mu\mathrm{m}^2$) by cleaning the surface of the NbN film, followed by the deposition of a superconducting NbTiN interlayer before a standard Au layer is deposited for the contacts [4, 6]. Using the same technology a $T_{\mathrm{rec,DSB}}$ of 900 K has been obtained in a twin-slot antenna coupled small NbN HEB ($1 \times 0.15\ \mu\mathrm{m}^2$) mixer at 1.6 THz [7]. Despite the fact that similar results have been obtained in devices fabricated in different runs, fluctuations in the sensitivity occur.

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We report here that the sensitivity of 'poor' NbN HEB mixers can be improved by annealing in vacuum. To understand the result, we characterize the devices with their dc properties and compare them with the mixer noise temperature and the mixer conversion gain.

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 $T_{\mathrm{c}}$ of 9.5 K, and coupled to a twin-slot antenna designed for 1.6 THz (see the inset of figure 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 applied to remove resist remnants followed by a brief *in situ* Ar sputter etch to clean the film surface. This is a critical technological step, which can result in 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 layer of 500 nm $SiO_2$ is sputtered on top of the active region of the HEB mixer, to prevent an ageing effect under normal laboratory conditions. Although several devices were measured, we focus here on one having a normal state resistance ($R_{\mathrm{N}}$) of 153 $\Omega$ at 16 K and a slightly reduced $T_{\mathrm{c}}$ of the NbN film of around 9 K.

  

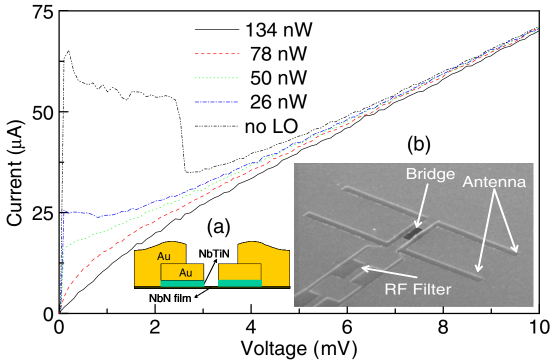


**Figure 1.** Current–voltage characteristics of a NbN HEB mixer without and with LO power, before annealing. In the inset: (a) a cross-section view of the bridge and the contacts of the HEB mixer; (b) a top view of the HEB mixer before the deposition of the $SiO_2$ layer, where the bridge, antenna,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

(This figure is in colour only in the electronic version)

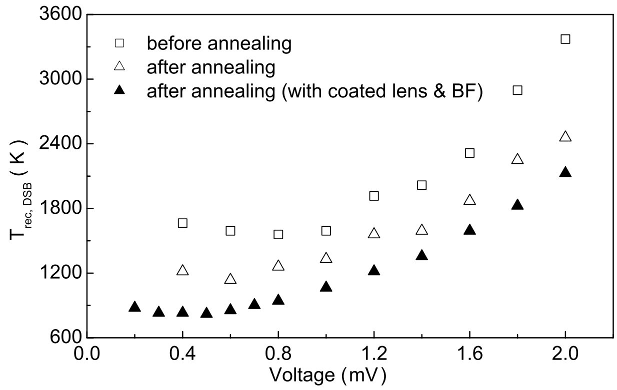


**Figure 2.** Receiver noise temperature (DSB) of the HEB mixer at 1.63 THz as a function of bias voltage obtained before and after annealing. Symbol notation: open squares and up-triangles—before and after annealing measured on an uncoated lens; closed up-triangles—after annealing measured using a coated lens and a cold bandpass filter (BF).

Annealing has been performed in an oven connected to a turbo pump. Before switching on and fixing it to 85 °C, the oven has been pumped for 24 h and the pressure reached is $10^{-5}$ mbar. Under these conditions the devices were annealed for 72 h.

We measure the receiver noise temperature, the gain, and the dc resistance versus temperature ($R(T)$) curve before and after annealing. We use a RF (radio frequency) test setup for a typical $Y$-factor measurement. A standard quasi-optical technique is applied to couple the RF signal from free space to the HEB. The HEB chip is glued to 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 to define 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 pass further into the lens through 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 it is attenuated with a rotatable grid. The IF signal 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.

In figure 1 we plot the current–voltage ($IV$) curves of the device, before annealing, without and with applying LO power. We also measured these curves after annealing and found a small reduction of the critical current from 68 to 65 $\mu$A and a small (4 Ω) increase of $R_N$. The change of $R_N$ is so small that no effects on the impedance matching between antenna and bolometer is expected. However, the pumped $IV$ curves are similar. In particular, the optimal $IV$ curve, where the lowest noise temperature is obtained, remains unchanged (although it depends on the LO power level). 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.

The $T_{rec,DSB}$ calculated according to the Callen–Welton definition [8] are plotted in figure 2 as a function of bias voltage at the optimal LO power before and after annealing. 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 $T_{rec,DSB}$ value after annealing decreases significantly over the whole voltage bias range. At the optimal bias point (0.6 mV), the $T_{rec,DSB}$ value decreases by 27% and becomes 1050 K, which is slightly lower than the previous best result for the case of the uncoated lens [7]. A similar improvement was observed in four other devices, showing a decrease of 25–30% in $T_{rec,DSB}$.

$T_{rec,DSB}$ reflects the effective noise temperature of the 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 figure 3. We observe that, after annealing, the mixer gain changes hardly. Around the optimal bias point, it increases by 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 an HEB equals $T_{mixer} \times G_{mixer}$, the annealing essentially reduces the intrinsic noise by 37%.

In analysing these results, we assume that the coupling of the RF signal via the antenna and transmission line into the HEB remains unchanged by the anneal. 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 annealing. Hence, we assume that the dominant cause of improvement is in changes of the device properties. For this reason, we compare the measured $R(T)$ characteristics before and after annealing (the main plot in figure 4). We observe three superconducting transitions in the $R(T)$ curve. According to our earlier study [10] we can define $T_c$ (the highest) for the bridge, $T_{c1}$ (the middle) for the

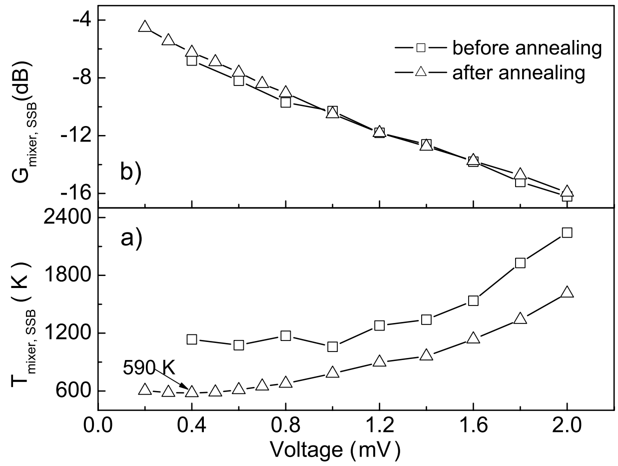


**Figure 3.** Mixer noise temperature (SSB) (a) and conversion gain (SSB) (b) of the HEB mixer as a function of bias voltage. The open squares denote the value before annealing; the open up-triangles denote the value after annealing.

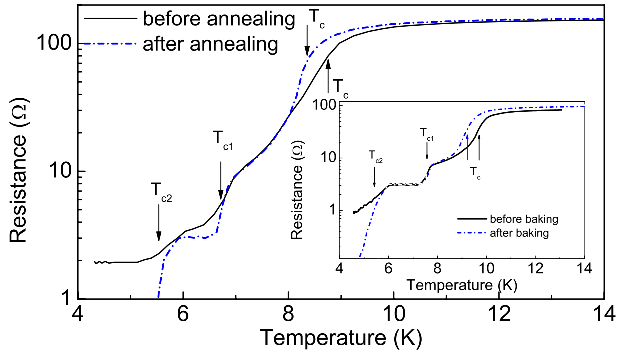


**Figure 4.** The resistance ($R$) of the HEB mixer as a function of temperature before (solid line) and after (dash–dotted line) annealing. $T_c$, $T_{c1}$, and $T_{c2}$ correspond to the transition temperature of the bridge, the contact pads and the transmission line/the RF filter structure, respectively (see figure 1). The inset shows the $R(T)$ of the device which does not show the sensitivity improvement after annealing.

**Table 1.** The critical temperature and the transition width of the NbN bridge ($T_c$, $\Delta T_c$), the contacts ($T_{c1}$, $\Delta T_{c1}$), and the 'RF filter structure' ($T_{c2}$, $\Delta T_{c2}$), before and after annealing.

| Parameter | Before annealing | After annealing |
|---|---|---|
| $T_c$ (K), $\Delta T_c$ (K) | 8.68, 1.55 | 8.37, 0.95 |
| $T_{c1}$ (K), $\Delta T_{c1}$ (K) | 6.94, 0.81 | 6.74, 0.33 |
| $T_{c2}$ (K), $\Delta T_{c2}$ (K) | 5.86, 0.76 | 5.53, 0.26 |

contact pads, and $T_{c2}$ (the lowest) for the transmission line/RF filter structure. Obviously, annealing affects all three aspects of the HEB devices. The effective NbN film has a reduced $T_c$ and a narrower transition $\Delta T_c$. The annealing also makes the superconducting transition in the $R(T)$ curve at $T_{c1}$ (the contacts) and $T_{c2}$ (the transmission line/RF filter structure) considerably sharper, and it leads to a small down shift in these values. A striking result is that after annealing a remaining resistance below $T_{c2}$, attributed to the transmission line/RF filter structure, disappears. In table 1 we list the various critical temperature values before and after annealing.

For comparison we briefly describe a similar annealing experiment with HEBs, which were already close to optimum performance. These devices show good sensitivity, comparable to results reported before [7]. The device also has a relatively sharp $R(T)$ curve similar to the one observed after annealing (see the inset of figure 4). Using these devices, the anneal gives either no change or improves the receiver noise temperature $T_{rec}$ slightly. The resistive transitions, before and after annealing, change in a different way. The $T_c$ moves slightly downwards but the visible part of the width of the transition $\Delta T_c$ hardly changes. On the other hand the transition associated with contacts responds differently. The critical temperatures $T_{c1}$ (the contacts) and $T_{c2}$ (RF wiring) do not change, neither do the resistance values, except for the RF wiring which also turns superconducting. Apparently, annealing does not alter the contacts in these optimal devices, whereas in the poorly performing devices annealing improves the contacts to become comparable to the best devices. This is reminiscent of previous results [4, 6] demonstrating that cleaning and contact structure influence the performance of the mixer significantly.

The resistive transition reflects changes in the devices, which carry over into the current–voltage characteristic in a complicated manner [11–13]. The latter is primarily controlled by the resistance of the NbN itself, characterized by $R(T)$. It is striking that the pumped current–voltage characteristics hardly change, suggesting that the $R(T)$ curves of the NbN itself are unchanged. However, the relevant $R(T)$ curves, which also depend on current, needed for a description of the $IV$ curves are not available.

It is worthwhile mentioning that the lumped element model [5] developed for an ideal HEB is not able to explain our experimental results. The inconsistency illustrates that a more realistic model for HEBs including important ingredients such as superconducting transition, the contacts, temperature profile, and noise is needed.

To determine the ultimate receiver noise temperature of the device after annealing, 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 a metal mesh RF bandpass filter with an effective bandwidth of 200 GHz centred 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 [14]. This effect, which can reduce the $Y$-factor, is particularly important in the case of the small volume HEBs. The measured new receiver noise temperature is also plotted in figure 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 figure 2), corresponding to 9 $h\nu/k_b$. This value is identical to the record sensitivity reported in a spiral-antenna coupled large ($4 \times 0.4\ \mu m^2$) HEB mixer at the same frequency [3, 15].

In conclusion, we have demonstrated that annealing can reduce the receiver noise temperature of NbN HEB mixers. The analysis shows that the anneal reduces the intrinsic noise of the mixer by 37%, but gives little effect on the mixer gain. The lowest SSB *mixer* noise temperature, which is the fundamental property of a mixer, is 590 K at 1.63 THz. Based on the $R(T)$ before and after annealing, we attribute the improvement in sensitivity to the changes in the contact/NbN interface of the devices. The measured lowest DSB *receiver* noise temperature is 700 K at the same frequency, which is uncorrected for any optical loss.

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