NbN phonon-cooled hot-electron bolometer mixer with additional diffusion cooling

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***Abstract*— We present low-noise and wide-bandwidth HEB mixers made from NbN-Au two-layer films *in situ* deposited on Si substrates. At 2.5 THz, the lowest double-side band receiver noise temperature was 750 K. The gain bandwidth measurements at T_c yielded a gain bandwidth of 6.5 GHz, exceeding by almost a factor of two the typical value of 3.5 GHz for phonon-cooled HEB mixers on Si substrates with no additional buffer layer. The record characteristics are attributed to the improved interface between the superconducting film and the gold contact pads.**

***Index Terms*—HEB mixer, phonon cooling, diffusion cooling, gain bandwidth, noise temperature**

I. INTRODUCTION

IN the terahertz range, most informative for the radio astronomy of the early universe, hot-electron bolometer (HEB) mixers have long ago established themselves as the best detectors because they offer the lowest noise temperature and a reasonably wide gain bandwidth [1-5]. Such instruments as HIFI, CASIMIR, and GREAT will be using HEB receivers to cover certain frequency bands above 1 THz [6, 7]. It should be noted, however, that all the HEB mixers that will be employed in the above instruments are phonon-cooled [8] and their IF bandwidth does not exceed 4 GHz. At the same time, the increase of the gain bandwidth and the reduction of the noise temperature are important both for continuum and spectroscopic observations. The traditional approach to increase the gain bandwidth has been to improve the acoustic transparency of the interface between the film and the substrate, and to decrease the film thickness. Using an appropriate substrate material or buffer layer allows increasing the gain bandwidth up to 3.2 GHz for waveguide HEBs [3] and 4.8 GHz for quasioptical HEBs [9]. Decreasing the film thickness yields further increase of the gain bandwidth up to 5.2 GHz [2] but for thicknesses less than 2.5 nm NbN loses its superconducting properties. It has been reported that the noise temperature and gain bandwidth of phonon-cooled HEB mixers can be improved by cleaning the interface between the superconducting film and the contact pads [4, 5].

Manuscript received 17 April 2009. This work was supported in part by Grant No. 07-02-13626-O from the Russian Foundation for Basic Research. Funding for M. F. was provided by Grant No. MK-3098.2008.2 from the President of the Russian Federation Foundation for Young Russian Scientists.

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With respect to the cooling mechanism, HEB mixers fall into two classes: phonon-cooled HEBs (PHEBs) [8] and diffusion-cooled HEBs (DHEBs) [10]. Which cooling mechanism dominates depends on the mixer length. If $L \ll L_{th} = (D\tau_{th})^{1/2}$ (L being the mixer length, D the diffusion coefficient, and τ_{th} the electron temperature relaxation time) the hot electrons will leave the mixer before being scattered by phonons. Diffusion cooling is effective, however, only if there is no additional energy barrier at the interface between the film and the contact pads. In the opposite case ($L \gg L_{th}$) the hot electrons will more likely give their excess energy to the lattice before leaving the film. Although Nb diffusion-cooled HEB mixers can offer a gain bandwidth as wide as 9 GHz [11] the decrease in the number of papers dedicated to this type of HEB mixer, together with the fact that mostly NbN phonon-cooled devices are installed in practical systems, suggests that there are serious problems in realizing low noise temperature and a wide gain bandwidth in the same device.

In this paper we propose a phonon-cooled NbN HEB mixer with additional cooling via diffusion of hot electrons into the normal contact pads. Being primarily of the phonon-cooled type, such a mixer offers simultaneously a record low noise temperature and a wide gain bandwidth. This is the first time a NbN HEB mixer with additional diffusion cooling has been proposed, and, as discussed in greater detail below, such a mixer has certain advantages compared to NbN PHEB and Nb DHEB counterparts.

II. DEVICE FABRICATION AND DC TESTING

The HEB mixers proposed in this paper were fabricated from NbN-Au two-layer films *in situ* deposited on high-resistivity polished Si substrates by DC magnetron sputtering. The films were patterned using e-beam lithography to obtain mixing elements with lengths 0.1 - 0.4 μm. Given an NbN film sheet resistance of about 500 Ω we chose a mixer length-to-width ratio of 0.1 to ensure better IF and RF match with the IF chain and the log-spiral antenna, respectively. Fig. 1 shows a SEM photograph of a part of an HEB device including the mixing element, the contact pads and a part of the spiral antenna. Also shown is a close-up of the inner part of the device including the mixing element and partly the contact pads. Referring to Fig. 2, our devices had two superconducting transitions: one at about 9 K of the mixer itself and the other around 7 K of the part of NbN film under the contacts due to the proximity effect. The critical current densities were about 4.5×10^6 A cm^{-2}, and the normal state resistances were 70-

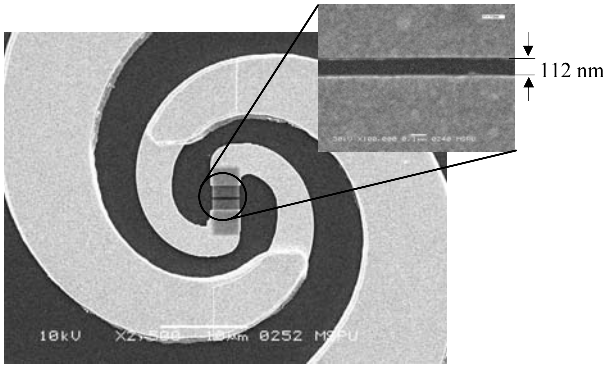

Fig. 1. A SEM photograph of an HEB device including the mixing element, the contact pads and a part of the spiral antenna. Also shown is a close-up of the inner part of the device including the mixing element and partly the contact pads; the length of the mixer is 112 nm.

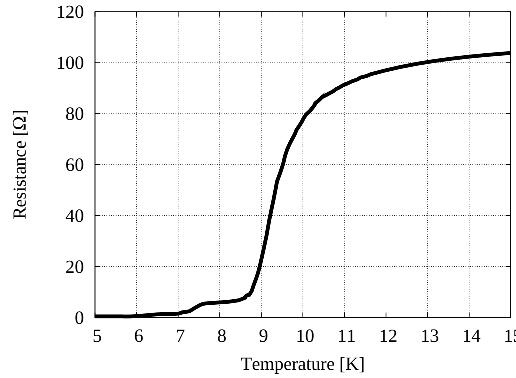

Fig. 2. Typical resistance-temperature curve for HEB mixers studied in this paper. As can be seen, besides the primary superconducting transition, there is also another one at lower temperature due to the proximity effect between the superconducting film and the normal contact pads.

80 Ω.

III. Experimental Setups

A. Gain bandwidth measurements

HEB mixers are described most simply by the uniform-heating model, which applies best when the device is operated at the superconducting transition temperature T_c. In this case the heat balance equations governing the dynamics of the superconducting film become linear and allow for an analytical solution which can be interpreted unambiguously [12]. That is why we chose to perform gain bandwidth measurements at T_c, where the superconducting energy gap is almost completely suppressed, and so the local oscillator frequency is not an issue.

For the gain bandwidth measurements we employed the standard technique with two monochromatic sources (in our case two backward-wave oscillators operating at about 300 GHz). An HEB mixer chip containing a log-spiral antenna with a mixing element at its apex was glued to an extended hemispherical Si lens and installed into a mixer block which was mounted onto the cold plate of a liquid helium cryostat. The HEB mixer was IF-coupled to a 3 cm long coplanar waveguide with a subsequent transition to a coaxial cable which delivered the IF signal out of the cryostat to a room-temperature broadband bias-tee followed by an amplifier with a pass-band of 0.1-12 GHz and a gain of about 36 dB. The amplifier output was fed to a spectrum analyzer. The IF chain was calibrated using a network analyzer.

B. Noise temperature measurements

The receiver noise temperature was measured at a local oscillator frequency of 2.5 THz and an ambient temperature of 4.2 K. A mixer block containing devices with dimensions 0.1-0.3 μm × 1-3 was mounted into a cryostat with a 0.5 mm thick high density polyethylene window and a Zitex-104 cold infrared filter. In order to reduce the direct detection effect [13] we mounted a 2-3 THz bandpass mesh filter on the cold plate. A gas discharge H_2O laser provided local oscillator drive at 2.5 THz, which was combined with radiation from a blackbody with the use of a 6 μm thick Mylar beam-splitter. The receiver back end comprised a wideband bias-tee followed by a cryogenic amplifier with a built-in isolator, together forming a unit with a gain of 30 dB over a bandwidth of 1-2 GHz. The room temperature part of the IF chain included two amplifiers, each with a gain of 30 dB and a bandwidth of 0.01-2 GHz, separated by a tunable 50-MHz bandpass filter. The output of the second room-temperature amplifier was fed to a square-law power detector followed by a high precision voltmeter.

IV. Experimental Results and Discussion

A. Gain bandwidth measurements

Our measurements showed that within an experimental error the noise temperature is independent of device dimentions so there is nothing special about the length 0.25 μm chosen for noise temperature measurements. However, to get a clear picture of the contribution of the diffusion channel, for the gain bandwidth measurements we chose devices with lengths from 0.12 μm to 0.35 μm. Fig. 3 shows the results of the gain bandwidth measurements for devices with the extreme lengths. Fitting the experimental data with

$$P(f_{IF}) = P_0/[1 + (f/f_{3dB})^2] \quad (1)$$

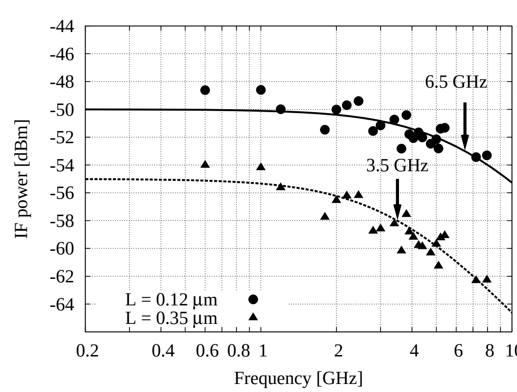

Fig. 3. The gain bandwidth measurement data for two HEB mixers with different lengths of the mixing element: 0.12 μm (circles) and 0.35 μm (triangles).

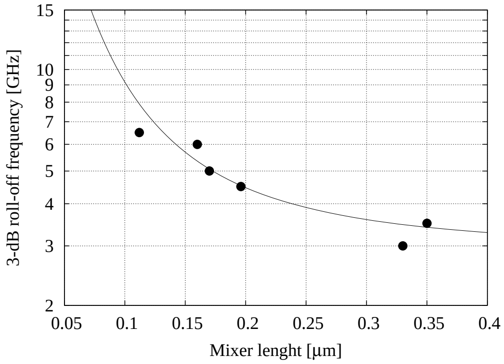

Fig. 4. The gain bandwidth as a function of the length of the mixing element. Solid curve is the theoretical dependence.

yields 3-dB rolloff frequencies of 6.5 GHz and 3.5 GHz for the lengths 0.12 µm and 0.35 µm respectively. The value 3.5 GHz is typical of PHEB mixers on Si substrates with no additional buffer layer.

For NbN HEB mixers studied in this paper, phonon cooling alone would result in a 3-dB rolloff of only about 3 GHz. That, combined with the experimental data, points to additional diffusion cooling, which is supported by theoretical estimations given below. As was shown in [14], the time constant of the DHEB equals

$$\tau_{diff} = L^2/\pi^2 D, \qquad (2)$$

where D is the diffusion coefficient of the material. In the case of a PHEB with additional diffusion cooling the total thermal conductance is $G_{tot} = G_{ph} + G_{diff}$, whence the mixer time constant is found to be

$$\tau_m = C_e/G_{tot} = (1/\tau_{ph} + 1/\tau_{diff})^{-1}, \qquad (3)$$

where C_e is the electronic heat capacity. Substitution of the relevant material parameters into Eqs. (2) and (3) yields 3-dB rolloff frequencies of 7.2 GHz and 3.5 GHz for mixer lengths of 0.12 µm and 0.35 µm respectively. Referring to Fig. 4, the gain bandwidth of several HEB mixers is shown as a function of the length of the mixing element; also shown is the dependence obtained with the use of Eq. (3). This result is of great fundamental and practical importance, since it provides a way to increase the gain bandwidth of NbN HEB mixers, which is limited by the electron-phonon interaction time and the escape time of nonequilibrium phonons into the substrate. The fact that at 4.2 K the film under the contact pads turns superconducting is not an issue at least for diffusion cooling, and measurements both at microwave [14] and terahertz [11] frequencies showed that the gain bandwidth results are in perfect agreement with equation (2). So, there is no doubt that further experiments at the low-noise operating point at terahertz frequencies and 4.2 K will show the contribution of the diffusion channel.

B. Noise temperature measurements

The noise temperature measurements were performed with the use of the standard Y-factor procedure. Although HEB mixers are known to suffer from the direct detection effect [4, 15], in our case this effect was found to contribute less than 5% to the receiver noise temperature in the IV plane due to the use of the mesh filter. Fig. 5 shows a family of the current-voltage characteristics of an HEB mixer with dimensions 0.25 µm × 2.5 µm taken at different levels of the local oscillator drive. The top curve is the least pumped one. Also shown is the receiver noise temperature at different operating points. The lowest value of the receiver noise temperature is 750 K, which is about 6 times $h\nu/k_B$ (k_B being Boltzmann's constant) at this frequency. As was shown by several authors [4, 5], the noise temperature can be lowered by decreasing RF loss in contacts. In situ gold contacts offer a simple and yet an essentially new solution to the problem of high contact resistance and RF loss.

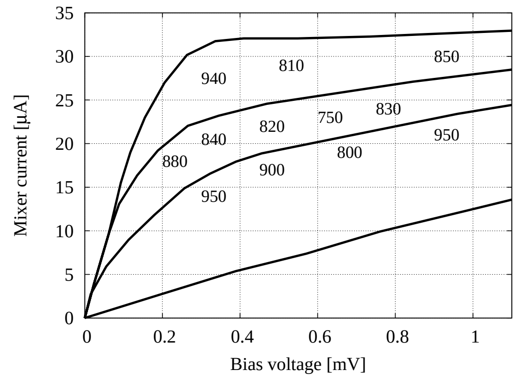

Fig. 5. A family of the current-voltage characteristics of an HEB mixer taken at different levels of the LO drive. The top curve is the least pumped one. Also shown is the receiver noise temperature at different operating points.

For HEB mixers shorter than 0.2 µm the absorbed LO power estimated with the use of the isothermal technique was found to be 160 nW/µm^2 (the film thickness is 3.5 nm) and to within an experimental error independent of the mixer length. This can be understood by noting that, for PHEB mixers, as the mixer dimensions are scaled down, say by a factor of k, such as to keep the length-to-width ratio constant, the absorbed LO power decreases by k^2. This continues until the mixer length becomes comparable to L_{th}. At that point diffusion cooling becomes effective, and since the diffusion time is proportional to the length squared, the rate of energy outflow is scaled by 1/ k^2. So in our case in the first approximation the amount of absorbed LO power should not depend on the mixer dimensions.

The absence of kinks on the IV curves and the fact that the receiver noise temperature does not change drastically with the change of the operating point demonstrates that the device is quite stable. That can be qualitatively understood by noting that if the mixer length were much shorter than the thermal healing length L_{th} the normal domain would collapse almost immediately after the formation, which would show itself as kinks on the IV curve. At the superconducting transition temperature, for the NbN mixers studied in this paper $L_{th} \approx 0.1$ µm, whereas for a Nb mixer the thermal healing length would be $L_{th} \approx 0.4$ µm. This means that although it is much easier to ensure the condition $L < L_{th}$ in a Nb mixer, the increase of the gain bandwidth will be achieved at the expense of the device stable performance.

We believe that allowing for atmospheric absorption and using an antireflection coating might bring the noise temperature down to about 550 K at 2.5 THz at the low-noise operating point.

V. Conclusion

We have demonstrated that the use of *in situ* gold yields an appreciable improvement of HEB mixer performance. A gain bandwidth as wide as 6.5 GHz was measured near the superconducting transition. This is almost twice as large as the usual value obtained for HEB mixers on Si substrates with *ex situ* gold contacts. The dependence of the gain bandwidth on the length of the mixing element further supports the conclusion that we have a PHEB mixer with additional diffusion cooling. At 2.5 THz the receiver offered a noise temperature of 750 K, which is 6 times $h\nu/k_B$. Eliminating contributions due to reflection off the Si lens and atmospheric loss should lower the receiver noise temperature by about 30%.

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