Doubling of sensitivity and bandwidth in phonon cooled hot electron bolometer mixers

J. J. A. Baselmans^{a)}

Space Research Organisation of the Netherlands (SRON), Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands

M. Hajenius and J. R. Gao

Space Research Organisation of the Netherlands (SRON), Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands and Faculty of Applied Sciences, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands

T. M. Klapwijk

Faculty of Applied Sciences, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands

P. A. J. de Korte

Space Research Organisation of the Netherlands (SRON), Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands

B. Voronov and G. Gol'tsman

Moscow State Pedagogical University, Moscow 119435, Russia

(Received 24 September 2003; accepted 9 January 2004)

We demonstrate that the performance of NbN lattice cooled hot electron bolometer mixers depends strongly on the interface quality between the bolometer and the contact structure. We show experimentally that *both* the receiver noise temperature and the gain bandwidth can be improved by more than a factor of 2 by cleaning the interface and adding an additional superconducting interlayer to the contact pad. Using this we obtain a double sideband receiver noise temperature $T_{N,DSB} = 950$ K at 2.5 THz and 4.3 K, uncorrected for losses in the optics. At the same bias point, we obtain an IF gain bandwidth of 6 GHz. © 2004 American Institute of Physics. [DOI: 10.1063/1.1667012]

In the past several years the development of THz receivers has mainly focused on hot electron bolometer (HEB) mixers.^{1,2} For practical applications NbN based phonon cooled HEB mixers are preferred. The current understanding of the device physics is based on a hot-spot description of the mixing process.³ Within this model the device performance depends on the intrinsic material parameters of the superconducting film but also on the exact shape of the temperature profile in the bolometer. The latter is a strong function of the (thermal) boundary conditions to the bolometer, which are formed by the contact pads (see Fig. 1). Hence it is surprising that virtually all improvement in sensitivity and bandwidth in the past several years of these mixers has originated solely from improvements in NbN thin film technology. Other parts of the device, in particular the bolometer–contact pad interface, have largely been ignored so far.

To clarify this we show, in Fig. 1, a cross-sectional drawing of the HEB mixer together with an electron microscope image of a real device. The HEB mixer consists of a 3.5-nm-thick NbN film on a Si substrate. The NbN film is covered with contact pads and an antenna structure. A 400-nm-wide opening between the contact pads forms the bolometer. The contact pad consists of ~60 nm Au (“2”) with a 5 nm Ti adhesion layer underneath (“1”). In the conventional fabrication process of a HEB mixer the deposition of the contact pads is done without any cleaning of the NbN film. Hence it is to be expected that a contact resistance exists between the NbN film and the contact pad. The presence of such a contact

resistance has been reported in the literature^{4,5} and explains the fact that the device resistance of these HEB mixers is always higher than expected based on the bolometer size and NbN sheet resistance. It also explains why the resistance versus temperature, $R(T)$, curve always shows only one superconducting transition. This implies a negligible superconducting proximity effect, which is only possible for very low

FIG. 1. (Top panel) A schematic cross-sectional drawing of the central device structure. (Bottom panel) Scanning electron microscope (SEM) image of one of the HEB mixers studied. Note that the SAL resist visible in the SEM image is not shown in the drawing.

^{a)}Electronic mail: j.baselmans@sron.nl

TABLE I. Description of the contact pad materials (denoted by “1” and “2” in Fig. 1) and the cleaning of the NbN–contact pad interface. Note that the O₂ plasma etch is *ex situ*, whereas the Ar⁺ etch is *in situ* with respect to the deposition of layers “1” and “2.” T_{c2} is the lowest critical temperature of the devices, associated with the transition of the contacts.

	Type I	Type II	Type III
Interface	O ₂ plasma	O ₂ plasma + Ar ⁺ etch	O ₂ plasma + Ar ⁺ etch
Layer “1”	5 nm Ti	5 nm Nb	10 nm NbTiN
Layer “2”	65 nm Au	45 nm Au	40 nm Au
R at 11 K	220±20 Ω	65±5 Ω	55±5 Ω
T_{c2}	9.5 K	5 K	7 K

interface transparencies.⁶ As stated before the performance of the HEB mixer depends strongly on the (thermal) boundary conditions. A contact resistance between the NbN film and the contact forms a barrier for the hot electrons diffusing out of the bolometer. It also changes the effective length of the bolometer, because the contact resistance determines the length over which RF current flows through the NbN film.⁷ An additional effect is that a contact resistance leads to bolometer-antenna impedance mismatch. All these issues have been noted before,^{4,5,7–11} however, they have never been addressed experimentally in detail.

In this letter we report the first dedicated experiment to study the effect of such a contact resistance on the mixer performance. To this purpose we have fabricated three different types of spiral antenna coupled HEB mixers in one single batch. The devices are fabricated on one single Si wafer that is covered at MSPU, Moscow with a 3.5 nm NbN film with $T_c = 9.7$ K. Device type I is identical to a conventionally fabricated NbN HEB mixer.^{4,5,8–11} No cleaning of the contact is performed here, except for a 6 s O₂ plasma etch to remove resist remnants prior to the contact pad deposition. For types II and III an additional physical etch using argon is performed to clean the NbN surface prior to the *in situ* deposition of the contact pads (argon etch parameters: 200 W; 8 μbar; 300 V bias, 15 s). As a consequence we expect the NbN–contact interface to be more transparent. However a higher interface transparency reduces the T_c of the contact structure.⁶ To counteract this we use a superconductor as layer “1” for types II and III. For type II 5 nm Nb is used as layer “1,” for type III 10 nm NbTiN is used as layer “1.” Details of the fabrication and dc characterization can be found in Ref. 12. The rest of the device fabrication is identical for all devices and similar to the conventional HEB mixer fabrication process.^{4,5,8–11}

From Table I it is clear that the device resistance is reduced from 220 Ω for type I to around 60 Ω for the other devices, which is roughly the value expected from the device size and NbN film sheet resistance. It is also clear that the critical temperature of the contact, T_{c2} , is reduced with respect to the critical temperature of the bolometer, T_{c1} . For type I we observe only one superconducting transition at 9.5 K, i.e., $T_{c1} = T_{c2} = 9.5$ K. For type II and III T_{c2} is lowered to 5 and 7 K, respectively. The higher T_{c2} of type III is associated with the higher intrinsic critical temperature of the 10 nm NbTiN layer “1” when compared to the 5 nm Nb layer “1” used in type II. Using the intrinsic critical temperatures of the films used for layer “1” together with the mea-

TABLE II. Measured results of the devices as described in Table I. $T_{N,DSB}$ is obtained at 2.5 THz using nonoptimized optics and $T_{N,rec,DSB}^{opt}$ is obtained (also at 2.5 THz) using optimized optics. D1 and D2 represent different devices of the same type. The gain bandwidth is measured at 600 GHz. In Fig. 2 these points are indicated for D2 of type III.

	Type I	Type II	Type III
$T_{N,rec,DSB}$ (D1)	4300 K	2500 K	1900 K
$T_{N,rec,DSB}$ (D2)	4600 K	2900 K	2050 K
Gain BW ^a	2 GHz	3 GHz	6 GHz
Gain BW ^b	5 GHz	5 GHz	6 GHz
$T_{N,rec,DSB}^{opt}$ (D1)	...	...	950 K

^aThe optimal bias point.

^bA high bias point.

sured values of T_{c2} we can estimate the transparency T_i of the interface (see Ref. 12 for details). We find $T_i \ll 0.005$ for type I, $T_i = 0.02$ – 0.03 for type II, and expect $T_i = 0.05$ for type III. This is because the interface preparation is identical and because the mismatch in Fermi velocities between NbN and Nb is larger than the mismatch between NbN and NbTiN.

The performance of the different HEB mixers is determined by measuring the double side band (DSB) receiver noise temperature $T_{N,DSB}$ and the IF gain bandwidth, i.e., the dependence of the conversion gain of the device with respect to the IF frequency. $T_{N,DSB}$ is determined, at 2.5 THz, by means of the standard Y-factor technique using a hot/cold load consisting of Eccosorb® at 295/77 K, placed 40 cm from the cryostat. We use the Callen and Welton definition to calculate the noise temperature from the Y-factor.¹³ To couple the radiation into the HEB mixer a quasi-optical setup is used in which the bolometer chip is glued to a hyper-hemispherical Si lens without antireflection coating. The lens is clamped to the mixer block, which is thermally anchored to the 4.2 K plate of a L–He cryostat. The mixer block temperature is 4.35 ± 0.05 K in all experiments. The cryostat has a 40-μm-thick Mylar window and 3 Zytex® G104 heat filters, one at 77 K and two at 4.2 K. As a local oscillator source we use a FIR laser at 2.5 THz, coupled into the cryostat by means of a 6 μm mylar beam splitter. The total losses in the optics are estimated to be 6.5 dB.¹⁴ The IF signal is amplified using a 1.1–1.8 GHz Berkshire® cryogenic low noise amplifier thermally anchored to the 4.2 K plate of the cryostat. The signal is further amplified using a broadband room temperature amplifier, filtered in an 80 MHz bandwidth and detected using a power meter. A calibration of the entire IF chain yields a total gain (of the two amplifiers) of 80 dB and a noise temperature of 4 K.

In Table II we show the measured results. It is obvious that type II and III devices have a lower $T_{N,DSB}$ than type I devices, the difference is more than a factor 2 between types I and III.¹⁵ Although the improvement is clear, the minimum noise temperature of type III is still larger than the best results obtained using conventional HEB mixers ($T_{N,DSB} = 1400$ K at 2.5 THz).⁸ The main reason for this is the high optical losses in our setup. By using an antireflection coated lens, only one zytex heat filter (at 77 K), a 3 μm beam splitter, and a direct hot/cold load only 10 cm from the cryostat window, we reduce the total optical losses to 3.5 dB, comparable to the loss reported in Ref. 11. The 3 dB im-

FIG. 2. (Top panel) Pumped and unpumped I - V curves together with the receiver noise temperature of D2 of type III at 2.5 THz, uncorrected for any optical losses. The absorbed LO power is estimated using the isothermal technique. (Bottom panel) The relative IF gain as a function of the IF frequency at optimum bias ("a" in the top panel) as well as at high bias ("b" in the top panel). The line represents a single pole response with a roll-off frequency of 6 GHz.

provement in the optical losses is expected to reduce the noise temperature by a factor 2.

We now measure again the $T_{N,DSB}$ of D1 of type III using the improved optics. We obtain, at 2.5 THz and 4.3 K, a receiver noise temperature uncorrected for optical losses as low as $T_{N,DSB} = 950$ K, corresponding to $8\hbar f/k$.¹⁶ The measured unpumped and pumped IV curves and noise temperatures using these optics are given in the top panel of Fig. 2.

The IF gain bandwidth is measured at 600 GHz using a BWO as LO source and a Carcinotron with doubler as the rf signal. The output power is amplified using a 0.1–8 GHz Miteq® cryogenic amplifier at 4.2 K with a noise temperature of about 100 K and 30 dB gain. At room temperature the signal is further amplified and measured using a spectrum analyzer. The upper frequency limit of our IF chain is measured to be 6 GHz using a calibrated noise source. We measure the bandwidth at two bias points: At the optimum bias point that yields the lowest $T_{N,DSB}$ ["a" in Table II] and at the same LO power but a higher dc voltage ("b" in Table II). The dc voltage is chosen such that $T_{N,DSB}$ is twice the value at optimum bias. The results are given in Table II and, for D2 of type III, in the bottom panel of Fig. 2.¹⁷ Two observations can be made here: First, the gain bandwidth at optimum bias increases from 2 to 6 GHz between types I and III. A gain bandwidth of 6 GHz is not only much larger than the best results obtained for a 3.5-nm-thick NbN HEB mixer on

Si,^{8,18} but even larger than the best result ever for a phonon cooled HEB mixer. This result, a gain bandwidth of 5.2 GHz, was obtained for a 2-nm-thick device on a substrate with a MgO buffer layer.¹⁹ Second, the expected bias dependence of the gain bandwidth seems to be virtually absent for type III. The reason for this is not clear, but might be related to the upper frequency limit of our IF chain. This in contrast with types I and II, where we do measure the expected dc bias dependence of the gain BW.

To conclude we have demonstrated that the interface between the bolometer itself and the contact structure play a crucial role in the mixer performance. Both the mixer sensitivity and IF gain bandwidth are improved by more than a factor of 2 by means of an *in situ* cleaning of the interface together with a deposition of an additional superconductor in the contact pad. The best device has $T_{N,DSB} = 950$ K at 2.5 THz with a gain bandwidth of 6 GHz at the same bias point.

The authors wish to thank H.F. Merkel, P. Khosropanah, S. Cheredinichenko, and M. Kroug for useful discussions and W.J. Vreeling for all practical assistance. This work is supported partly by the European Space Agency (ESA) under Contract No. 11653/95/NL/PB.

¹E. M. Gershenzon, G. N. Goltsman, I. G. Gogidze, A. I. Eliantev, B. S. Karasik, and A. D. Semenov, *Sov. Phys. Supercond.* **3**, 1582 (1990).

²D. E. Prober, *Appl. Phys. Lett.* **62**, 2119 (1993).

³D. Wilms Floet, E. Miedema, T. M. Klapwijk, and J. R. Gao, *Appl. Phys. Lett.* **74**, 433 (1999).

⁴A. D. Semenov, H.-W. Hübers, J. Schubert, G. N. Gol'tsman, A. I. Eliantiev, B. M. Voronov, and E. M. Gershenzon, *J. Appl. Phys.* **88**, 6758 (2000).

⁵P. Khosropanah, T. Berg, S. Cherednichenko, H. Merkel, S. Svechnikov, V. Drakinsky, E. Kollberg, and G. Gol'tsman, *Proceedings of EUCAS*, 2003.

⁶A. A. Golubov, *Superconducting Superlattices and Microstructures*, edited by I. Bozovic, [Proc. SPIE **215**, 353 1994].

⁷H. F. Merkel, P. Khosropanah, K. Sigfrid Yngvesson, S. Cherdinichenko, M. Kroug, A. Adam, and E. L. Kollberg, 12th International Symposium on Space Tetrahertz Technology, San Diego, CA, 2001, p. 55.

⁸S. Cherednichenko, P. Khosropanah, E. Kollberg, M. Kroug, and H. Merkel, *Physica C* **372–376**, 407 (2002).

⁹S. Miki, Y. Uzawa, A. Kawakami, and Z. Wang, *IEEE Trans. Appl. Supercond.* **11**, 175 (2001).

¹⁰P. Khosropanah and H. Merkel (private communication).

¹¹M. Kroug, Ph.D. thesis, Chalmers University of Technology, Goteborg, Sweden, 2001.

¹²M. Hajenius, J. J. A. Baselmans, J. R. Gao, T. M. Klapwijk, P. A. J. de Korte, B. Voronov, and G. Goltsman, 14th International Symposium on Space Tetrahertz Technology, Tucson, AZ, 22–24 April 2003.

¹³A. R. Kerr, *IEEE Trans. Microwave Theory Tech.* **47–3**, 325 (1999).

¹⁴The 6.5 dB optical losses consist of 3.3 dB for the beam splitter, window, and heat filters (measured values), 1.1 dB for lens reflection, 1.2 dB for lens absorption and lens/antenna mismatch, and 0.9 dB for the air path between the hot/cold load and the cryostat.

¹⁵Note that a type I device of another batch with the same geometry, but with a resistance at 20 K of 157Ω has shown a receiver noise temperature of 2800 K using the identical measurement setup.

¹⁶The device quoted in Ref. 15 would have given a receiver noise temperature of 1400 K if it was measured using the same optimized setup as used for D1 of geometry III quoted here.

¹⁷The results in Fig. 2 are obtained between 0.1 and 6 GHz. Higher frequency measurements are not possible in our present setup.

¹⁸P. Yagoubov, M. Kroug, H. Merkel, E. Kollberg, G. Gol'tsman, S. Svechnikov, and E. Gershenzon, *Appl. Phys. Lett.* **73**, 2814 (1998).

¹⁹Y. B. Vachtomin, M. I. Finkel, S. V. Antipov, B. M. Voronov, K. V. Smirnov, N. S. Kaurova, V. N. Drakinski, and G. N. Gol'tsman, 13th International Symposium on Space Tetrahertz Technology, Harvard University, Cambridge, MA, 26–28 May 2002, p. 259.