Optimal Choice of Material for HEB Superconducting Mixers

Boris S. Karasik*, William R. McGrath, and Rolf A. Wyss

Center for Space Microelectronics Technology, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Abstract—We demonstrate that a potential distinction in ultimate performance of phonon-cooled and diffusion-cooled HEB mixers is not due to the cooling mechanisms but rather due to the different properties of available superconductors. The only available material for a phonon-cooled mixer with sufficiently large IF bandwidth (~4 GHz) is NbN, whereas a variety of clean materials (e.g., Nb, NbC, Al) are suitable for a diffusion-cooled mixer. For a readily achievable device length of 0.1 μm for example, the IF bandwidth can be ≥ 10 GHz. The requirement of low local oscillator (LO) power can also be more easily met in diffusion-cooled devices by selection of a material with lower critical temperature and low density of electron states. In contrast, the parameters in the NbN-based mixer cannot be widely varied because of the high resistivity and high transition temperature of the material and the necessity of using ultrathin films. Given the limited availability of LO power from compact solid-state sources at frequencies above 1 THz, a diffusion-cooled mixer based on aluminum is a very attractive choice for low-background radioastronomy applications.

I. INTRODUCTION

Hot-electron bolometric (HEB) superconducting mixers are becoming the desirable choice for use in radioastronomy heterodyne receivers at frequencies above 1 THz. The development effort of the last several years has resulted in the achievement of excellent device characteristics both for phonon-cooled and diffusion-cooled mixers. HEB receivers hold the low-noise record, by a wide margin, at 2.5 THz [1] and successfully compete with SIS mixers at frequencies around 1 THz.

In addition to the noise temperature, the local oscillator (LO) power and the mixer IF bandwidth are the most important characteristics which must meet certain requirements set by a specific application and/or availability of sufficiently powerful LO sources. A typical amount of LO power absorbed in the device is approximately 50-100 nW for many HEB mixers. One should account for 5-10 dB of embedding circuit and optical losses typical for terahertz mixers. While this LO requirement is lower than any competing device technology, there are nonetheless no tunable solid state sources available to pump HEB mixers at frequencies above 1.5 THz. Though an instant bandwidth of ~10 GHz seems to be sufficient for many practical spectroscopy applications, the unavailability of tunable THz LO sources may require much larger bandwidth for an HEB mixer. This is because a CO₂-pumped FIR laser may be the only option for an LO, and most often the available laser emission lines are many GHz separated from the particular spectral line of interest.

Currently LO source technology is not as well developed as mixer technology and this puts further demands for improvement of HEB mixers in terms of decreasing the LO power requirements and increasing the IF bandwidth. Also, since theoretically the HEB mixers can achieve quantum limited noise performance, it is of practical interest to find a way to achieve this limiting performance. In general, there is always a tradeoff between mixer characteristics when one attempts to optimize a particular characteristic of the mixer. The relationships between the mixer characteristics depend on the cooling mechanism dominating in the HEB device. A proper choice of the device material can create a more optimal combination of mixer parameters. In the present paper we evaluate several superconducting materials with the goal of achieving optimal mixer performance and show what limitations are set by the cooling mechanism.

II. COOLING MECHANISMS IN HEB DEVICES

Any HEB mixer device is a strip of superconducting film deposited onto a dielectric substrate between two normal-metal contacts. Depending on the device size, either phonon or diffusion cooling dominates in the thermal energy removal from a hot-electron bolometer.

The first mechanism takes place in a relatively large devices with a length \( L > (D \tau_{ep})^{1/2} \) (\( D \) is the electron diffusion constant, \( \tau_{ep} \) is the electron-phonon interaction time). In this case the energy deposited into the electron subsystem by radiation or dc current is removed by means of electron-phonon collisions and consequent escape of nonequilibrium phonons into the substrate. The characteristic time of the phonon escape (proportional to the film thickness), \( \tau_{es} \), must be much shorter than the phonon-electron energy transfer time \( \tau_{ep} = \tau_{ep}^{ch}/C_e \) (\( C_e, \tau_{ep}^{ch} \) are the electron and phonon specific heats respectively). At helium temperatures \( \tau_{ep} < \tau_{es} \) and the film must be very thin in order that all the energy will be transferred from electrons to the substrate. An intense "back and forth" exchange of energy between electrons and phonons

* Electronic mail: Boris.Karasik@jpl.nasa.gov

Manuscript received September 15, 1998.

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Fig. I. Typical values of electron-phonon relaxation time for various superconducting films. The data points are shown at the critical temperatures of the materials. NbN could theoretically provide an effective bandwidth of ~10 GHz, however the effect of a finite phonon escape time slows down the relaxation in these films. See explanation in Section III.
Prober [16], uses electron diffusion in submicron size devices will be described in greater detail in the following section. Make sure that $\tau_e \ll \tau_{ph}$. This case was successfully time to provide the bandwidth of several GHz is NbN [5]. It is known material which has a sufficiently short electron-phonon time in Nb is too long to be useful for most practical applications (see Fig. 2). For operation of the low- $T_c$ hot electron bolometer as a mixer one should avoid this situation and make sure that $\tau_e \ll \tau_{ph}$. This case was successfully implemented in Nb films with thickness $d<10$ nm [3,4]. However, the electron-phonon time in Nb is too long to be useful for most practical applications (see Fig. 2). The same applies for many other superconducting materials. The only known material which has a sufficiently short electron-phonon time to provide the bandwidth of several GHz is NbN [5]. It will be described in greater detail in the following section.

Another cooling mechanism for HEB mixers proposed by Prober [16], uses electron diffusion in submicron size devices will result in effective slowing down of the relaxation process, decrease of required LO power for the mixer, and increase of the noise temperature. In fact, the case when $\tau_e > \tau_{ph}$ is typical for conventional low- $T_c$ superconducting bolometers which are not used as heterodyne mixers, and for high- $T_c$ superconducting HEB mixers (more details on the latter case can be found in [2]). For operation of the low- $T_c$ hot electron bolometer as a mixer one should avoid this situation and make sure that $\tau_e \ll \tau_{ph}$. The case was successfully applied for many other superconducting materials. The only known material which has a sufficiently short electron-phonon time to provide the bandwidth of several GHz is NbN [5]. It will be described in greater detail in the following section.

Fig. 2. The crossover from phonon cooling to diffusion cooling in NbC HEB devices of [17]. The data points following the $T^3$ law represent the electron-phonon time in a long device. The relaxation time in shorter devices has much weaker temperature dependence since the contribution of electron diffusion is larger.

The same film approximately follow the expected $L^{-2}$ as shown in Fig. 5. This dependence was previously shown at microwave frequencies below 20 GHz [18], and we show here the first confirmation at submillimeter frequencies.

The diffusion cooling regime can be achieved in most materials as long as the device is made sufficiently short. It is simpler to observe however when the diffusion constant $D\geq 1$ cm$^2$/s. For smaller diffusivities, the device length needs to be less than 0.1 $\mu$m in order to provide a practical (ie: > 1 GHz) bandwidth. Such short device sizes are difficult to achieve. Fortunately, there is a variety of materials where large diffusivities can be easily obtained. As seen in Fig. 4, Nb, NbC, and Al all have $D\geq 1$ cm$^2$/s. Many data points have been obtained for Nb microdevices with $D=1$-2 cm$^2$/s.

The data for the devices of different length made from the same film approximately follow the expected $L^{-2}$ as shown in Fig. 5. This dependence was previously shown at microwave frequencies below 20 GHz [18], and we show here the first confirmation at submillimeter frequencies.

For $D=10$ cm$^2$/s (a typical value for aluminum) and $L=0.1$ $\mu$m, the calculated diffusion time is about 0.1 ps which corresponds to an effective mixer bandwidth of 160 GHz. Even taking into account the difference between the theory and experiment, a bandwidth of several tens GHz seems to be quite possible.

Another cooling mechanism for HEB mixers proposed by Prober [16], uses electron diffusion in submicron size devices

III. BANDWIDTH

The diffusion cooling regime can be achieved in most materials as long as the device is made sufficiently short. It is simpler to observe however when the diffusion constant $D\geq 1$ cm$^2$/s. For smaller diffusivities, the device length needs to be less than 0.1 $\mu$m in order to provide a practical (ie: > 1 GHz) bandwidth. Such short device sizes are difficult to achieve. Fortunately, there is a variety of materials where large diffusivities can be easily obtained. As seen in Fig. 4, Nb, NbC, and Al all have $D\geq 1$ cm$^2$/s. Many data points have been obtained for Nb microdevices with $D=1$-2 cm$^2$/s.

The data for the devices of different length made from the same film approximately follow the expected $L^{-2}$ as shown in Fig. 5. This dependence was previously shown at microwave frequencies below 20 GHz [18], and we show here the first confirmation at submillimeter frequencies.

For $D=10$ cm$^2$/s (a typical value for aluminum) and $L=0.1$ $\mu$m, the calculated diffusion time is about 0.1 ps which corresponds to an effective mixer bandwidth of 160 GHz. Even taking into account the difference between the theory and experiment, a bandwidth of several tens GHz seems to be quite possible.
A large range of diffusion constants gives flexibility in adjusting the mixer resistance to a desirable value. Indeed, if one tries to increase the bandwidth by using very clean film, it may happen that the resistivity will be so low that the mixer device will be mismatched with the planar antenna impedance. Such a situation is more likely in Nb which has a higher density of electron states \( N_e \) (\( \langle \rho^2 \rangle = N_e \rho^2 D \)) than Al and NbC where the density of states is three times lower than in Nb (see Fig. 4). Therefore one can use cleaner films (= larger bandwidths) of these materials, while maintaining at the same time a suitable resistance for matching to rf embedding circuits. Niobium nitride is the only material which has a short enough electron-phonon relaxation time and, therefore, is useful for fabrication of HEB mixers. There is indirect evidence that the intrinsic bandwidth set by the electron-phonon relaxation time at the critical temperature of 8-9 K is \( \approx 10 \text{ GHz} \). The corresponding relaxation time \( \tau_{\text{ph}} = 13 \text{ ps} \) [19] is very short and since \( c_e = 0.3c_p \) the phonon-electron relaxation time \( \tau_{\text{pe}} = 40 \text{ ps} \). Even for the thinnest NbN films used in the recent experiments [19,20] the phonon escape time is also 40 ps. It means that the phonons do not remove the thermal energy from the film but rather exchange it with electrons. As a result, the relaxation slows down and the apparent bandwidth is smaller than that implied by \( \tau_{\text{pe}} \), i.e. 4 GHz instead of 10 GHz. This situation can be adequately described by introduction of both electron and phonon temperatures different from the temperature of substrate. Any further increase of bandwidth in NbN seems to be problematic because: (a) it is hardly possible to fabricate even thinner (<3 nm) high quality NbN films; and (b) electron diffusion still does not play a role in the relaxation since \( \tau_D \) is much larger than \( \tau_{\text{ph}} \).

**IV. ULTIMATE NOISE PERFORMANCE AND LOCAL OSCILLATOR POWER**

According to theory [21] the best HEB mixer performance takes place when the thermal fluctuation noise dominates over the Johnson noise. This is a case of a strong self-heating in the mixer device which is possible if the device has a sharp superconducting transition and large critical current density. Under these circumstances assuming that the device operates at temperature \( T_c < T_c \), the SSB mixer noise temperature, \( T_{\text{m}} \), is given by the following expression:

\[
T_M = (n+2)T_c,
\]

where \( n \) is the exponent in the temperature dependence of the electron temperature relaxation time. For phonon-cooled devices it is an electron-phonon time: \( n = 1.6 \) for NbN, \( n = 2 \) for Nb, \( n = 3 \) for NbC. For diffusion cooled devices \( n = 0 \). The limits given by (1) are shown in Fig. 6 (horizontal lines). One can see that the theoretical limit for Al is many times lower than that for NbN. The theory of [21] does not consider any quantum phenomena though the quantum noise limit will be important at THz frequencies. A simplistic empirical correction can be made by adding one quantum contribution, \( h/\kappa \), to the limit of (1). As a result the difference in \( T_M \) between Al and NbN HEB mixer becomes smaller but is still significant.

**V. PERFORMANCE TRADEOFFS**

As can be seen from the above considerations, for a phonon-cooled HEB mixer, the IF bandwidth depends on the electron-phonon interaction time which is temperature dependent. Since a material with a relatively high \( T_c \) such as NbN is required, a wide bandwidth means higher noise temperature (1) and higher LO power (2). Thus these mixer characteristics must be traded against each other to optimize the performance for this type of mixer.
The art tunable solid state LO sources. In particular, properties of commonly used superconducting thin films, qualities for optimization of HEB mixers for use in aluminum films appear to possess desirable and necessary noise performance. However, due to the characteristic power, bandwidth, and noise. Developing HEB devices with type of mixer thus provides more flexibility in optimization for a particular application.

VI. CONCLUSION

We have shown that both phonon-cooled and diffusion-cooled HEB mixers are predicted to give quantum limited noise performance. However, due to the characteristic properties of commonly used superconducting thin films, diffusion-cooled HEB provide more flexibility to meet the various needs of practical applications in regards to LO power, bandwidth, and noise. Developing HEB devices with lower critical temperature may allow the mixer to more readily reach quantum-limited noise performance at THz frequencies and meet the power requirements for the state-of-the-art tunable solid state LO sources. In particular, aluminum films appear to possess desirable and necessary qualities for optimization of HEB mixers for use in demanding radioastronomy applications.

REFERENCES

[1] B.S. Karasik, M.C. Gaidis, W.R. McGrath, B. Bumble, and H.G. LeDuc, “Low noise in a diffusion-cooled hot-electron mixer at 2.5 Thz”, Appl. Phys. Lett., vol. 71, pp. 1567-1569, September 1997.
[2] B.S. Karasik, W.R. McGrath and M.C. Gaidis, “High-Tc hot-electron superconducting mixer for terahertz applications”, J. Appl. Phys., vol. 81, pp. 1581-1589, February 1997.
[3] E.M. Gershenzon, M.E. Gershenzon, G.N. Gol’tsman, A.M. Lyut’kin, A.D. Semenov, and A.V. Sergeev, “Electron-phonon interaction in ultrathin Nb films”, Zh. Exp. Teor. Fiz., vol. 97, pp. 901-911 (1990) JETP, vol. 70, pp. 505-515 (1990).
[4] E.M. Gershenzon, G.N. Gol’tsman, I.G. Gogidze, Yu.P. Gousev, A.I. Elantev, B.S. Karasik and A.D. Semenov, “Millimeter and submillimeter range mixer based on electron heating of superconducting films in the resistive state”, Sverkhprovodnost’ (RIAE) vol. 3, pp. 2143-2160 (1990) Superconductivity, vol. 3, pp. 1382-1397 (1990).
[5] Yu.P. Gousev, A.D. Semenov, G.N. Gol’tsman, A.V. Sergeev, and E.M. Gershenzon, “Electron-phonon interaction in disordered NbN films”, Physica B, vol. 194, Part I, pp. 1355-1356, February 1994.
[6] T.M. Klapwijk, P.A. van der Plas, and G.E. Mooij, “Electron-electron scattering in dirty three-dimensional aluminum films”, Phys. Rev. B vol. 33, pp. 1474-1477, January 1986.
[7] Y. Bryunseraede, M. Gijs, C. van Haesendonck, and G. Deutscher, “Magnetoresistance measurement of the electron inelastic scattering time in two-dimensional Al films in the presence of superconducting fluctuations”, Phys. Rev. Lett., vol. 50, pp. 277-281, January 1983.
[8] P. Satyanan and D.E. Prober, “Inelastic electron scattering mechanism in clean aluminum films”, Phys. Rev. B, vol. 29, pp. 3733-3736, March 1984.
[9] J.M. Gordon and A.M. Goldman, “Electron inelastic scattering in aluminum films and wires at temperatures near the superconducting transition”, Phys. Rev. B, vol. 34, pp. 1500-1507, August 1986.
[10] B. Shinozaki, T. Kawaguti, Y. Fujimori, “Inelastic electron scattering time of superconducting aluminum films superposed with normal metal”, J. Phys. Soc. Japan, vol. 61, pp. 3678-3688, October 1992.
[11] E.M. Gershenzon, G.N. Gol’tsman, V.D. Potapov, and A.V. Sergeev, “Restriction of microwave enhancement of superconductivity in impure superconductors due to electron-electron interaction”, Solid State Com., vol. 75, pp. 639-641 (1990).
[12] J.W.P. Hsu and A. Kapitulnik, Phys. Rev. B, “Superconducting transition, fluctuation, and vortex motion in a two-dimensional single-crystal Nb film”, vol. 45, pp. 4819-4835, March 1992.
[13] S.I. Park and T.H. Geballe, “Tc depression in thin Nb films”, Physica B & C, vol. 135, pp. 108-112 (1985).
[14] B.J. Dalrymple, S.A. Wolf, A.C. Entlich, and D.J. Gillespie, “Inelastic electron lifetime in niobium films”, Phys. Rev. B, vol. 33, pp. 7514-7519, June 1986.
[15] B. Bumble and H.G. LeDuc, “Fabrication of a diffusion cooled hot-electron bolometer for THz mixing applications”, IEEE Tran. Appl. Supercond., vol. 7, pp. 3500-3563, June 1997.
[16] D.E. Prober, “Superconducting terahertz mixer using a transition-edge microbolometer”, Appl. Phys. Lett., vol. 62, pp. 2119-2121, April 1993.
[17] B.S. Karasik, K.S. Il’in, E.V. Pechen’, and S.I. Krasnosvolodsev, “Diffusion cooling mechanism in a hot-electron NbC microbolometer mixer”, Appl. Phys. Lett., vol. 68, pp. 2285-2287, April 1996.
[18] P.J. Burke, R.J. Schoelkopf, D.E. Prober, A. Skalare, W.R. McGrath, B. Bumble, and H.G. LeDuc, “Length scaling of bandwidth and noise in hot-electron superconducting mixers”, Appl. Phys. Lett., vol. 68, 3344-3346, June 1996.
[19] S. Cherednichenko, P. Yagoubov, K. Il’in, G. Gol’tsman, and E. Gershenzon, “Large bandwidth of NbN phonon-cooled hot-electron bolometer mixers on sapphire substrates”, Proc. 6th Int. Symp. on Space Terahertz Technology, 25-27 March 1997, Harvard University, Cambridge, MA, pp. 245-257.
[20] P. Yagoubov, M. Kroug, H. Merkel, E. Kolberg, G. Gol’tsman, A. Lipatov, S. Svechnikov, and E. Gershenzon, “Quasipotential NbN phonon-cooled hot-electron bolometric mixers with low optimal local oscillator power”, Proc. 9th Int. Symp. on Space Terahertz Technology, 17-19 March 1998, Pasadena Hilton, Pasadena, CA., pp. 131-140.
[21] B.S. Karasik and A.I. Elantev, "Noise Temperature Limit of a Superconducting Hot Electron Bolometer Mixer", Appl. Phys. Lett., vol. 68, pp. 853-855, February 1996, "Analysis of the noise performance of a hot-electron superconducting bolometer mixer", Proc. 6th Int. Symp. on Space Terahertz Technology, 21-23 March 1995, Caltech, Pasadena, pp. 229-246.
[22] R.S. Nebosis, A.D. Semenov, Yu P. Gousev, and K.F. Renk, "Rigorous analysis of a superconducting hot-electron bolometer mixer: theory and comparison with experiment", Proc. 7th Int. Symp. Space Terahertz Technology, 12-14 March 1996, University of Virginia, Charlottesville, VA, pp. 601-613.
[23] P.J. Burke, "High frequency electron dynamics in thin film superconductors and applications to fast, sensitive THz detectors", Ph.D. Dissertation, Yale University, December 1997.