# NOVEL HOT-ELECTRON BOLOMETER MIXERS FOR SUBMILLIMETER APPLICATIONS: AN OVERVIEW OF RECENT DEVELOPMENTS

*William R. McGrath*

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

## 1. INTRODUCTION

Recently there has been a resurgence of interest in bolometers as heterodyne mixers at submillimeter wavelengths. This is due primarily to two new and innovative concepts [1,2] which result in bolometers with response times fast enough to allow for intermediate frequencies (IF) of 1 GHz - 10 GHz, as well as low mixer noise temperatures. These IF's are high enough for practical spectroscopy applications and thus these bolometers need to be seriously considered as heterodyne sensors. In this paper I will review briefly review the basics of bolometer mixers. Then an overview will be given of the basic operation of the new high speed bolometers, along with a few recent results which demonstrate the performance. Finally, the role these sensors may be expected to fulfill will be discussed. I should emphasize that this paper is meant to provide a brief introduction to these new bolometer mixers, and reference will be made to the recent literature for the interested reader who wishes to delve more deeply into the details. This is not a review article, but rather an overview of recent developments, so no attempt is made to give a complete listing of results and publications.

## 2. BOLOMETER MIXERS

Bolometers have been used occasionally as heterodyne mixers primarily because of the advantages of high frequency operation (bolometers can be operated at millimeter through submillimeter wavelengths) as well as high sensitivity with near-quantum limited noise. Additionally, bolometers are simple square-law or total-power detectors. There is no instantaneous response at the rf as with an electronic mixer, such as a Schottky diode or SIS tunnel junction. There is also no harmonic response. The principle disadvantage of the bolometer mixer is the slow thermal response time. This limits the IF to low values, usually of order MHz. In general this is too low to be useful for many remote-sensing applications involving molecular line spectroscopy such as radioastronomy, atmospheric chemistry, and planetary science.

The limitation placed on the IF by the thermal response time can be understood by considering the basic operation of a bolometer mixer. The two basic elements of a bolometer are shown in figure 1. There is an element which absorbs the incident rf power, typically an absorbing film. The absorber has a thermal heat capacity C, and as it absorbs power its temperature T increases. The absorber is connected to a thermal bath temperature $T_{bath}$ by a thermal conductance G. The thermal response time is given by $\tau_{\theta} = C / G$, and represents the characteristic time over which the temperature of the bolometer can change for a sudden change in incident rf power.

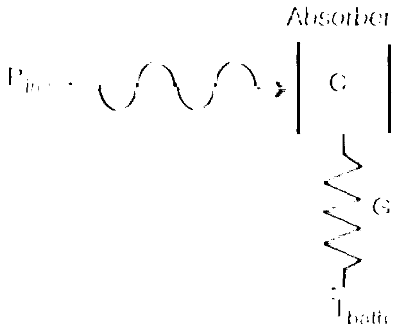

Fig. 1: Basic elements of a bolometer. C is the heat capacity of the absorber typically a thin film. G is the thermal conductance to the bath temperature. $P_{inc}$ is the incident rf power.

To operate the bolometer in a heterodyne mode, a local oscillator voltage, $V_{LO}$, at frequency $\omega_{LO}$ and a signal voltage, $V_S$, at frequency $\omega_S$ are applied to the absorber, which for simplicity we take to be a thin film of resistance $R_{\theta}$. The resulting dissipated power is:

$$P(t) = P_{LO} + P_S + 2(P_{LO}P_S)^{1/2} \cos(\omega_{IF} t) \qquad (1)$$

where $\omega_{IF} = \omega_{LO} - \omega_S$ is the IF frequency, and $P_{LO} = (V_{LO}^2 / 2R_{\theta})$ and $P_S = (V_S^2 / 2R_{\theta})$ are the LO power and signal power respectively dissipated in the bolometer. The bolometer is not fast enough to follow the rf, so the power dissipated at these frequencies is the time averaged value. However, if the IF is low enough, the bolometer can follow this variation, so there can be a time dependent term at this frequency. The *Voltage Responsivity*, S, of the bolometer [3] gives the change in voltage across the bolometer for a change in absorbed power, and hence can be used to estimate the IF voltage amplitude:

$$V_{IF} = S \cdot 2(P_{LO}P_s)^{1/2} \qquad (\ )$$

The responsivity is given by:

$$S = I\,(dR/dT)\,/\,[G\cdot(1 + \omega_{IF}^2\,\tau_{th}^2)^{1/2}$$

where I is the bias current through the resistive film, and dR/dT is the derivitive of film resistance with temperature. Thus for low enough IF, that is $\omega_{IF}^2\,\tau_{th}^2 < 1$, the bolometer can follow the IF power swing; but for $\omega_{IF}^2\,\tau_{th}^2 > 1$, the IF voltage will decrease and hence the conversion efficiency of the mixer will decrease. As mentioned above, $\tau_{th}$ for many conventional bolometers is large enough that the IF is limited to undesirably low values. However, the two new bolometers discussed below address this issue.

## 3. NEW APPROACHES

Recently, two new approaches [1,2] have been proposed for bolometers with very short thermal response times and hence a high IF rolloff frequency. Both bolometers utilize the resistive transition in a superconductive thin film which results in a large dR/dT and hence high responsivity. What is new however, is that these devices make use of very thin films: about 10 nm for Nb or NbN. Such thin films have a very high scattering rate due to surface effects and hence a short electron mean free path $\ell$, which is about 1 nm - 10 nm. In these films, it is found that the electron-electron interaction is enhanced, resulting in a short electron-electron interaction time: $\tau_{ee} \propto \ell$; and the electron phonon interaction is weakened: $\tau_{ep} \propto \ell^{-1}$ [2] . Since the electrons can reach thermal equilibrium at a temerature different from the lattice temperature. Thus when absorbing rf power, the electrons can warm up relative to the lattice temperature. The electrical resistance in the film depends on the electron temperature and such a device is known as a hot-electron bolometer. Since only the electrons are heated, the heat capacity C can be very small, especially for a submicron-sized device. In addition, the hot-electron bolometer mixers discussed below employ novel mechanisms for cooling the electrons which results in a high thermal conductance and hence an overall short thermal relaxation time.

Before describing the details of the bolometers, it is useful to list the important advantages of these novel devices:

1) The thermal response time is very fast: ≈ 10's ps. Thus IF's of 1 GHz - 10 GHz can be achieved.

2) These bolometer mixers should operate well to very high frequency: several THz. There is no energy gap limitation as in an SIS mixer. In fact, rf power is absorbed more uniformly above the energy gap frequency.

3) The mixer noise temperature is very low: near-quantum limited.

4) Very low LO power is required: nW's - µW's. This is comparable to the requirements for SIS mixers and is an important issue at high submillimeter wave frequencies where LO power is difficult to generate.

5) The rf impedance of the device is essentially resistive and is determined by the geometry of the film; that is, the number of squares in a small strip. Typical values range from 20 Ω to 200 Ω. This greatly simplifies the rf circuit design. Unlike a Schottky diode or SIS tunnel junction, there are no parasitic reactances to tune out. The real rf resistance of the bolometer should be independent of frequency from about the energy gap frequency up to a frequency corresponding to the inverse electron electron elastic scattering time (about $10^{-15}$ sec) which is approximately 160 THz [1].

6) In addition, these devices make use of existing materials and fabrication techniques: Nb, NbN, YBCO; micron-scale photolithography, and/or submicron E-beam lithography.

## 4. DIFFUSION-COOLED HOT-ELECTRON BOLOMETER MIXER

Figure 2 shows the basic geometry of this bolometer mixer which was proposed by D. Prober in 1993 [1]. The unique feature of this device is that it uses the rapid diffusion of hot electrons out of a submicron length strip (or microbridge) of superconductor into normal metal contacts as the cooling mechanism, or thermal conductance. In order for diffusion to dominate, over electron-phonon interactions, as the cooling mechanism, it is necessary for the microbridge to be short. The appropriate length L can be estimated [1] from the expression:

$$) \,\tau_{ee})^{1/2} \qquad (4)$$

where D is the diffusion constant, and $\tau_{ee}$ is the electron-electron inelastic ("energy sharing") interaction time. Basically when an electron absorbs energy from an rf photon, it shares its energy in a time $\tau_{ee}$ and also diffuses a distance L/2. A hot electron in the middle of the bridge can thus go L/2 left or right. At that point, it encounters the normal metal contact which serves as a heat sink. These pads at the end of the microbridge must be normal metal since Andreev reflection [4] at the energy gap in a thick superconducting film would trap the hot-electrons inside the microbridge and substantially slow the response of the device. The electron-electron interaction time can be estimated from [5]:

$$\tau_{ee} = \quad 10^{\text{[illegible]}} R_s T_c)^{\text{[illegible]}} \qquad (5)$$

where $R_s$ is the surface resistance and $T_c$ is the superconductive transition temperature of the thin film. For the very thin ( dirty limit ) film used here, $R_s$ is larger and $T_c$ is smaller than the bulk values. For a 10 nm Nb film for example, $R_s \approx 20\ \Omega/\mathrm{sq}$, $T_c \approx 5$ K, and the width of the transition is $\Delta T_c \approx 0.5$ K. Substituting these values into eqn (4) and eqn (5), yields a length $L \approx 0.2\ \mu m$. The microbridge can be somewhat longer (with a corresponding increase in $\tau_{th}$), but should be less than $2(D\tau_{ep})^{1/2}$ where $\tau_{ep}$ is the electron-phonon interaction interaction time. For this length and longer the electrons will remain in the bridge long enough to produce phonons which can alter the mode of operation (see section 5).

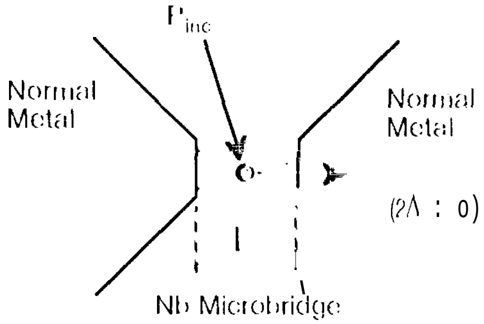

Fig. 2: Basic geometry of the diffusion-cooled hot-electron bolometer mixer.

The thermal response time can be calculated from the usual expression:

$$\tau_{th} = C/G \tag{6}$$

The thermal capacitance is given by the electron specific heat [6]:

$$C = \gamma T V \tag{7}$$

where $\gamma = 700\ \mathrm{J/K^2m^3}$ for Nb, T is the electron temperature (which is always about $T_c$ in a transition edge device), and V is the device volume. The thermal conductance G is given by the Wiedemann-Franz Law [6]. This law states that the ratio of thermal conductance to electrical conductance is proportional to temperature, if the electrons carry both the electrical *current and the thermal* current, which is the case for the diffusion-cooled microbridge. Thus:

$$G = (\pi^2/3)(k_B/q_e)^2 (T/R_{eff}) \tag{8}$$

where $k_B$ is Boltzmann's constant, $q_e$ is the charge on the electron, T is the temperature ($\approx T_c$) and $R_{eff}$ is the effective electrical resistance of the microbridge: $R_{eff} \approx R_n / 12$ [1]. $R_n$ is the DC resistance of the microbridge for T just above $T_c$. The factor 1/12 arises because heat flows symmetrically out both ends of the microbridge.

For an actual bridge [7] with dimensions width = 0.14 µm, length = 0.28 µm, thickness = 10 nm and $R_n = 30\ \Omega$, the estimated response time is 30 psec. The 3 dB IF rolloff frequency for the mixer conversion efficiency is then given by:

$$IF_{rolloff} = (2 \cdot \pi \cdot \tau_{th})^{-1} \tag{9}$$

*which is about 5 GHz in this case.* However, due to self-heating effects [3] ( and to a lesser extent by IF impedance mismatch effects [8] ) the *thermal conductance* is reduced to a lower effective value:

$$G_{eff} = G(1-A) \tag{10}$$

where typically $0.1 < A < 0.9$ for thermally stable operation. Thus the value of $IF_{roll}$ can actually be in the range of about 2-5 GHz, which allows for IF's commonly used in heterodyne instruments.

Now we will estimate the mixer conversion efficiency η, the double-sideband receiver noise temperature $T_R$(DSB), and the LO power $P_{LO}$. The conversion efficiency for a bolometer *mixer* was *originally* worked out in detail by Arams et al [9] in 1966 and recently discussed in connection with these new hot-electron bolometers [8]. For convenience, we will follow the simplified approach given by Prober [1]. The conversion can be estimated using the voltage responsivity of the bolometer and the IF power amplitude. The result is:

$$\eta = P_{IF} / P_{RF} = [I^2 (dR/dT)^2 / G^2] \cdot [P_{LO} / 2R] \tag{11}$$

( note: this expression is valid for $\omega_{IF}\tau_{th} << 1$ ). For equal DC power ( $P_{DC} = I^2R$) and LO power dissipated in the bolometer, η(SSB)= 1/8 = -9 dB ( note that η > 0 dB may be possible under some conditions [8] ) It can be shown that the conversion efficiency in this case is independent of L, the length of the *microbridge* [1]. However, the response time $\tau_{th} \propto L^2$, thus $IF_{rolloff} \propto 1/L^2$. Hence, as expected for a device that relies on *diffusion out the ends, shorter* is better for high speed. However, there is no sacrifice in conversion efficiency. While decreasing L will increase G and hence reduce the bolometric responsivity, in the heterodyne mode this can be compensated by increasing the LO power. Thus it is possible to have a bolometer mixer which is both *fast* and *sensitive.*

The best optimization of LO and DC power is a topic of current discussion [1,10]. In practice, the bolometer is thermally biased at a temperature somewhat below $T_c$, then a combination of DC and LO power is used to heat the electrons up to $T_c$. Prober [1] suggests setting $T_{bath} \approx T_c - \Delta T_c/2$ (that is, just below the transition width) and then applying enough LO to heat the electrons up by $\Delta T_c/4$ along with an equal *amount* of DC power. The LO power can then be readily approximated by $P_{LO} \approx \Delta T_c\, G / 4$ which is 4 nW for a 50 Ω microbridge with $\Delta T_c = 0.5$ K. Karasik and

Elantev [10] however suggest that the bath temperature should be made low and then the LO power should heat the electrons from $T_{bath}$ up to $T_c$-$\Delta T_c/2$ and the DC power should then raise the temperature by $\Delta T_c/2$ in order to reach $T_c$. This implies an LO power of ≈ 70 nW for the same microbridge with $T_{bath} \approx 2.5$ K and $T_c \approx 5$ K. Since both the conversion efficiency and mixer noise improve with increasing LO power [10], the higher value may be desirable. In either case, the LO power requirement is extremely low; equal or less than that required for a submillimeter wave SIS mixer.

It is currently accepted that the main contributions to the noise in a bolometer mixer are due to Johnson noise and electron temperature fluctuation noise [11]. The latter being dominant. The Johnson noise temperature is, of course, $T_c$ and arises from the film resistance at the transition temperature. The electron temperature fluctuation noise arises from the thermodynamic energy fluctuations in an electron gas at an average thermodynamic temperature $T_c$. The RMS electron temperature fluctuation can be expressed as [8]:

$$\Delta T_c = 4\,k\;\; T^2\;\; G \qquad 12$$

This yields a DSB mixer input noise temperarture of $T_c^2\, G\, /\, P_{LO}$ according to Karasik and Elantev [10]. For the LO power level considered by Prober, this reduces to $T_c^2/\Delta T_c$. The resulting DSB receiver noise temperature can be expressed as [1]:

$$T_R\,(DSB) = [\,(\,T_c^2\,/\,\Delta T_c) + T_c + T_{IF}\,]\,/\,\eta \qquad (13)$$

where $T_{IF}$ is the IF amplifier system noise temperature. Thus for $T_c \approx$ 5 K, $\Delta T_c \approx$ 0.5 K, $T_{IF} \approx$ 4 K, and $\eta$(DSB) ≈ -7 dB (ie: 6 dB intrinsic mixer conversion loss and 1 dB of receiver optical path loss), we get $T_R$(DSB) ≈ 295 K. However, reducing $T_C$ just 1 K ( a slightly thinner film ) yields $T_R$(DSB) ≈ 200 K. This performance becomes competitive with current state-of-the-art SIS receivers near frequencies of 500 GHz - 600 GHz. However, for the bolometer mixer there is no inherent frequency dependence of the performance above the energy gap frequency (except of course for the linear frequency dependence set by the quantum limit [12] ). The same noise temperature, 200 K, should be possible at 0.5 THz or several THz (mechanisms which may ultimately limit the high frequency performance will be briefly discussed below).

To date, the diffusion-cooled hot-electron bolometer mixer has been rapidly developed by the Jet Propulsion Laboratory in collaboration with Yale University [7,13,14] (no other groups have yet reported results on this new device). A Nb device with dimensions 0.15 µm wide, 0.28 µm long, and 10 nm thick was tested in a waveguide mixer mount in a receiver at an LO frequency of 530 GHz ( see references 7 and 14 for a complete discussion of these results ). This LO frequency is well above the gap frequency of ≈ 400 GHz for this thin Nb film with $T_c \approx 5.3$ K and $\Delta T_c \approx 0.5$ 1 K. The DSB receiver noise temperature is 650 K at an IF of 1.4 GHz. The estimated DSB mixer noise temperature is 560 K and mixer conversion efficiency is about -11 dB. The calculated receiver noise temperature is 570 K - 750 K (depending on the exact choice of $\Delta T_c$ from the R-T curve and using $\eta$ ≈ -11 dB), and similarly the predicted mixer conversion efficiency is about -9 dB [15]. Thus the calculated values agree well with experiment. The IF rolloff frequency was measured to be about 2 GHz, which represents superior performence for a low-noise bolometer mixer. This performance is comparable to the more mature submillimeter wave SIS receivers. It is thus clear from these results that this device works well as a submillimeter wave heterodyne mixer.

## 5. ELECTRON-PHONON COOLED HOT-ELECTRON BOLOMETER MIXER

Figure 3 shows the basic geometry of this bolometer which was proposed by E. Gershenzon, et al in 1990 [2]. The basic operation of this bolometer can be understood from fig. 3(b). An incident rf photon imparts its energy to an electron in the film. In a short time $\tau_{ee}$ this electron shares its energy with other electrons. The cumulative effect of absorbed rf power and the energy sharing process (ie: the enhanced electron-electron interaction) in these ultra-thin films is to create a hot-electron distribution. Then in a time $\tau_{ep}$ a hot electron creates a phonon which then escapes ballistically, for a sufficiently thin film, to the substrate in a short time $\tau_{ES}$. In order for the hot-electron bolometric mechanism to proceed in this manner, there are some constraints which must be met. First $\tau_{ee} << \tau_{ep}$ to allow the electrons to heat up from absorbed power. This is usually satisfied for a thin (dirty limit) film at low temperatures T < 10 K ($\tau_{ee} \approx 10^{-10}$ sec to $10^{-12}$ sec) [16]. Next it is important for $\tau_{ES} << \tau_{pe}$, where $\tau_{pe}$ is the phonon-electron interaction time . That is, the phonons must escape to the substrate before they interact back with other electrons. This requires that the film be very thin since[2,16,17]:

$$\tau_{ES} = 4\,d\,C_e\,/\;\; v\,\alpha \qquad (14)$$

where d is the film thickness, $C_e$ and $C_{ph}$ are the electron and phonon specific heats respectively, v is the velocity of sound, and $\alpha$ is the coefficient of transmission of a phonon through the film-substrate interface. The thermal response time of the bolometer can then be written as:

$$\tau_{th} = \tau_{ep} + \tau_{ES} \qquad (15)$$

Thus the limiting speed of this type of bolometer is set by $\tau_{ep}$ ( this limit requires $\tau_{ES} << \tau_{ep}$ and thus the films should be thin, the phonon transmission at the substrate interface high, and the thermal conductivity of the substrate should also be high so that it remains a constant temperature bath). For a Nb bolometer, $\tau_{ep} \approx$ 1 ns and hence $IF_{rolloff} \approx$ 160 MHz, which is higher than most bolometer mixers but still too low for many practical applications. For NbN operated at 7 K - 8 K, $\tau_{ep} \approx 15$ ps and hence $IF_{rolloff} \approx 10$ GHz. This is of course high enough to be of practical value.

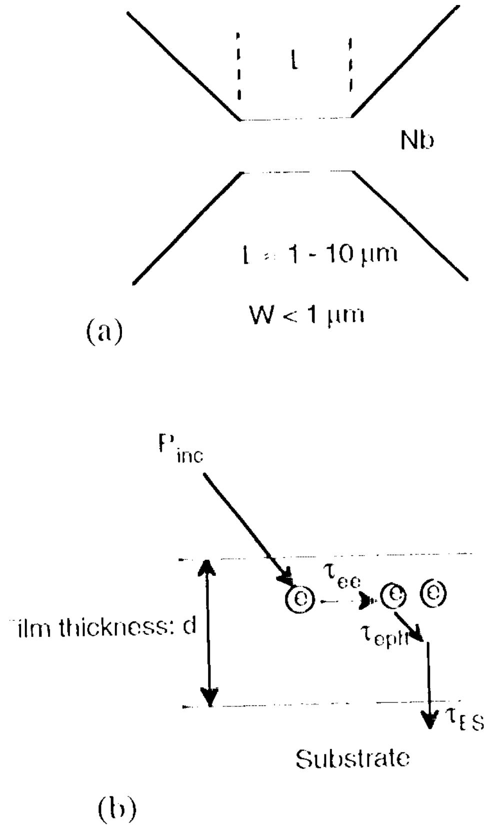

Fig. 3: Basic geometry of electron-phonon cooled bolometer mixer. (a) Top view showing geometry of microbridge. (b) Cross sectional view showing schematically the electron-phonon interactions described in the text.

The LO power requirements can be estimated in the same way as discussed in the previous section except G is now given by the electron-phonon thermal conductance ( $G = 4x10^4 \bullet T^3 \bullet V$ for thin Nb films [2], for example ). It should be noted that G in this case depends on the volume V of the microbridge and thus it is advantageous to keep the volume small. The width of the microbridge should be less than about 1 μm to avoid a backflow of phonons from the substrate [2]. Then for a given film surface resistance $R_S$ the length is chosen to give the appropriate resistance for an rf match to the mixer embedding circuit (waveguide, planar antenna, etc...). A typical size is 1 μm x 5 μm. The LO power then required for a Nb bolometer mixer is about 50 70 nW ( $T_c = 4$ K and $\Delta T_c = 0.5$ K ); and for NbN, $P_{LO} \approx$ 0.5-1 μW ( $T_c = 7$ K and $\Delta T_c = 0.5$ K ). These are extremely low and therefore very desirable for submillimeter operation.

The mixer noise temperature and conversion efficiency are calculated in the same way as previously discussed. However, the more detailed analysis in [8] suggests that under certain conditions, conversion efficiency greater than unity is possible. Also, as mentioned above, the exact choice of DC and LO power to optimize the mixer is still being theoretically analyzed.

Recent results have shown that the electron-phonon cooled bolometer mixer performs very well. Measurements on a Nb bolometer mixer [8] at an LO frequency of 20 GHz gave conversion efficiencies between -1 dB and -7 dB, an IF rolloff of 80-100 MHz, and an LO power of about 40 nW. These results are in close agreement with expected values. In addition, an NbN bolometer mixer operated in a waveguide mount at 100 GHz [18] has demonstrated an IF rolloff as high as 1.5-2 GHz, and a DSB receiver noise temperature of 450 K. This is extremely good performance, and is suitable for practical low-background spectroscopy applications.

Also, high-Tc yttrium-barium-copper oxide (YBCO) bolometers have been investigated [19-21] at wavelengths of 0.8 μm (375 THz), 1.56 μm (192 THz), and 10.6 μm (28 THz). The goal of these investigations was to demonstrate the high speed hot-electron response and the heterodyne mixing process (no attempt was made to produce a fully optimized mixer at such high frequencies, so the estimated conversion efficiency was low). Heterodyne mixing was clearly demonstrated in thin YBCO films with an IF up to 18 GHz (the limit of the measurement system). Since these bolometers operate at 80-90 K, the phonons play a more significant role which changes the device physics as compared to the low-Tc case (see references 10, 18-20 for a more detailed discussion).

## 6. DISCUSSION

The recent innovations in transition-edge hot-electron bolometers (micron and submicron sized, thin, dirty films) have led to ultra-fast, sensitive devices which are competitive as heterodyne mixers. Recent measurements have proven the concepts and even shown competitive performance. However, the most complete mixer measurement to date have been mainly below 1 THz ( except for the YBCO bolometer mixer tests ) where there already exist state-of-the-art SIS receivers with very low noise. These new bolometer mixers will play an important role at frequencies well above 1 THz where SIS and Schottky receivers become either extremely difficult or impossible (ie: above the energy gap frequency of NbN for example) to operate. In addition, the high-Tc bolometer will be useful in applications where sensitivity can be traded off against cooling requirements, as in a space-based mission.

Important development issues must be addressed for each bolometer. The diffusion-cooled bolometer will need improved submicron definition and alignment of the normal metal contacts. Also, low-resistance normal-to-superconductor contacts are required. For the electron-phonon cooled bolometer, the phonon reflection at the film substrate interface must be minimized. This will be particularly important for materials like NbN (which have a high upper limit to the IF rolloff) which can react strongly with common rf substrates such as quartz, thereby producing a poor interface. In addition, both types of bolometers are resistive at the rf, so a very broadband match, to a planar antenna for example, should be easily achieved. The rf bandwidth can however be so broad that the mixer will be easily saturated. Unlike the common situation for an electronic mixer with reactive parasitics where the goal is to achieve a broadband rf match, these bolometer mixers will probably require bandpass filters at high submillimeter wave frequencies.

Finally, since the likely role for these bolometer mixers will be at very high frequencies, it is important to test as soon as possible the prediction that the performance is independent of frequency. Certain mechanisms may affect the high frequency performance. A high energy rf photon (several THz) will produce a high energy electron in the superconductive film. This hot electron can then either share its energy with other electrons, or break Cooper pairs, or produce hot phonons. In any case, the film will absorb rf power, but if the energy escapes, for example by the hot phonons rapidly leaving the film, before it is shared with the electron gas, then the electrons will not heat as efficiently and the sensitivity of the mixer will decrease. However, investigations of phonon processes in thin Nb films [22] suggest this will not be the case. The expectation is that the performance will not degrade until at least several THz. These detectors should thus have a significant impact on the field of THz heterodyne sensors.

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