Wide-Bandwidth Electron Bolometric Mixers: A 2DEG Prototype and Potential for Low-Noise THz Receivers

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***Abstract*— This paper presents a new type of electron bolometric ("hot electron") mixer. We have demonstrated a three order of magnitude improvement in the bandwidth compared with previously known types of electron bolometric mixers, by using the two-dimensional electron gas (2DEG) medium at the hetero-interface between AlGaAs and GaAs. We have tested both in-house MOCVD-grown material, and MBE material, with similar results. The conversion loss (L_c) at 94 GHz is presently 18 dB for a mixer operating at 20 K, and calculations indicate that L_c can be decreased to about 10 dB in future devices. Calculated and measured curves of L_c versus P_{LO}, and I_{DC}, respectively, agree well. We argue that there are several different configurations of electron bolometric mixers, which will all show wide bandwidth, and that these devices are likely to become important as low-noise THz receivers in the future.**

I. Introduction

Development of lower noise receivers for the frequency range approaching, and exceeding, 1 THz is presently an important goal. Realizing this goal will expand our ability to employ sensitive superheterodyne detectors in this region, with good spectral resolution, especially from space-based platforms. Such systems are required for remote sensing as well as astronomical investigations. A review of the receiver noise temperatures so far achieved in this range is given in Fig. 1. Above 500 GHz, the lowest noise temperatures are still the ones reported for the electron bolometric mixer [1], for which the active medium is a piece of bulk, low-doped, InSb. This mixer originated from physics-related work in the 1960s [2], [3], and was analyzed by Arams *et al.* from an engineering point of view [4]. Phillips and Jefferts [5] developed a complete receiver for radio astronomy use in the millimeter wave range. It is plausible to attribute the low noise temperature to the bulk nature of the InSb mixer, which leads to a very small parasitic reactance. In contrast, severe requirements have to be imposed on the size of SIS or Schottky devices for use at these frequencies.

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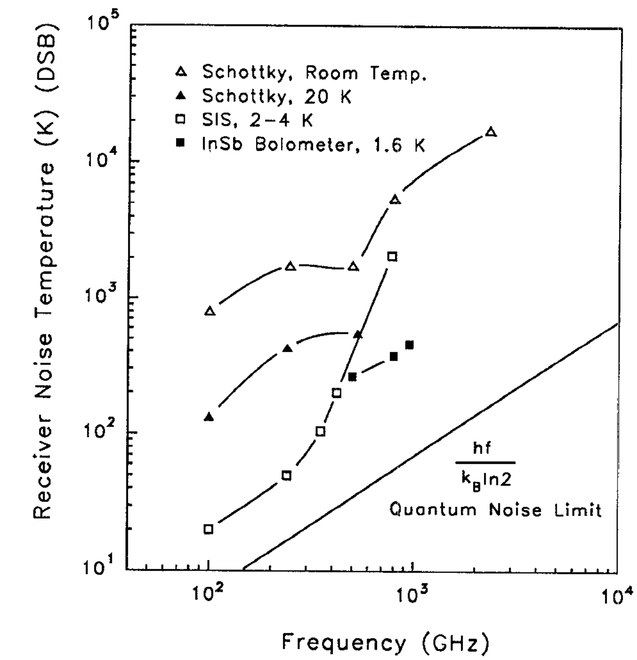

Fig. 1. Receiver noise temperatures in the MM and Sub-MM range, versus frequency. The InSb noise temperatures are from Brown *et al* [1]. Recent data for the SIS and Schottky barrier receivers are primarily based on data presented by several authors at the Third International Symposium on Space Terahertz Technology.

The InSb mixer has one major draw-back, i.e., its very narrow bandwidth (about 1 MHz), which has limited its use in practical systems. A similar narrow bandwidth was obtained for a bulk GaAs mixer [6]. Somewhat wider bandwidths can be realized in these mixers at higher operating temperatures, but only with a substantial decrease in conversion efficiency, and associated rise in noise temperature. It was perhaps then easy to conclude that all hot electron mixers should be characterized by a narrow bandwidth. As originally pointed out by Smith *et al.* [7], it does not appear that this limitation should apply to all hot electron mixers, however. The crucial point is to make use of a nonlinear element based on the two-dimensional electron gas (2DEG) medium at a heterojunction interface, for example formed between AlGaAs and GaAs. In this paper, we report experimental results on a prototype electron bolometric mixer at 94 GHz using this medium, with a bandwidth improvement by three orders of magnitude compared with the earlier hot electron devices, and conversion loss of 18 dB. We have obtained good agreement between measured and calculated conversion loss, and project that it should be feasible to decrease the conversion loss to about 10 dB, comparable to that of InSb mixers. We also expect the receiver noise temperature of the new 2DEG mixer to be in the same range as that of the InSb mixer. So far no measurements have been performed of this quantity, but a simplified estimate in Section V predicts a DSB temperature of 450 K. The data achieved for the prototype mixer indicate that it should be feasible to produce practical hot electron mixers in the THz frequency region by extending these techniques.

In this paper, we briefly review the properties of hot electron mixers, and present our measured and calculated data. Two different modes of operation have been attempted:

1) Mode I: This is the type of mixer which we have demonstrated. It operates at temperatures up to about 100 K, and presently requires LO power of the order of a milliwatt. Its operation is based on the rapid temperature dependence of the electron mobility, near $T = 100$ K, which is due to optical phonon emission.

2) Mode II: The Mode II mixer was proposed by Smith *et al.* [7], operates at about 4 K, and requires the use of a moderately large magnetic field. There are two distinct magnetically biased hot electron mixers: *Mode IIa* is tuned to cyclotron resonance at the frequency to be detected with the help of a fairly low magnetic field ($< 1T$). So far, this type of device has been demonstrated in the 2DEG medium as a detector, but not as a mixer. It is the mode in which the InSb mixer operates above 500 GHz [1]. The LO power is predicted to be in the microwatt range, or lower. We have also discovered a new mode of operation (*Mode IIb*), which uses a somewhat larger magnetic field, 1-4 Tesla, i.e., in the region in which Shubnikov-DeHaas oscillations are seen for the DC resistance. Again, only detection has been demonstrated so far, using the 2DEG device. The physical principles of operation of Mode IIB are not yet clear.

Finally, we briefly compare the 2DEG mixers with other potentially interesting hot electron mixers using thin film superconductors, which also employ a quasi-two dimensional geometry. We argue that there is a large class of different hot electron media, which can be used for mixing with bandwidths of about 1 GHz, or greater, with potential for use in the THz region.

II. Frequency Conversion in Hot Electron Mixers

Basic Mechanism

Hot electron mixers employ a nonlinear (electron) bolometer device of the type shown in Fig. 2. In electron bolometers, the electron gas is heated by the applied power (dc and/or RF) to a temperature, T_e, above the lattice temperature, T_0. The advantage of an electron bolometer, compared with a standard bolometer, which relies on heating of the lattice, is that the specific heat of the electrons is much smaller than that of the lattice. The basic nonlinearity which gives rise to mixing in hot electron mixers relies on the fact that the resistance (R_B) of the device is a function of the electron temperature, and therefore also a function of the total power applied (P).

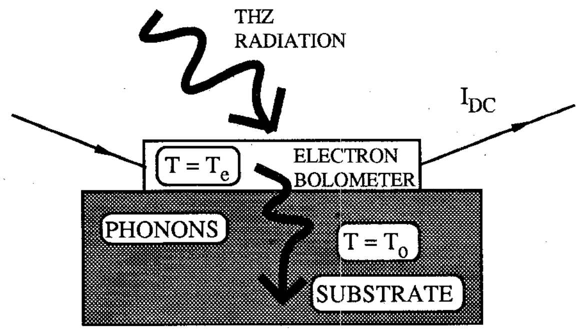

Fig. 2. Schematic drawing of a generic electron bolometer device.

Response Time and Bandwidth

The maximum rate at which the resistance of a hot electron bolometer can vary is determined by the response time of the electron gas. This response time is in turn given by the effective time for energy transfer from the electron gas to the lattice, which is basically the same as the energy relaxation time, τ_e. As two millimeter wave frequencies, $f_{\rm LO}$ and f_s, are applied to such a device, there is a relatively slow variation of the total, smoothed, instantaneous power at the frequency $|f_{\rm LO} - f_s| = f_{\rm IF}$. The resistance of the device will vary at this frequency, giving rise to an IF voltage across the device if current bias is applied. The maximum rate at which the resistance can vary is about $1/\tau_e$, and consequently we find that the IF band extends from dc to a maximum 3 dB bandwidth given by [4]:

$$B \approx 1/2\pi\tau_e \tag{1}$$

It should be clear that a bolometric mixer is fundamentally different from, for example, a Schottky-barrier diode mixer. One important feature is that no harmonic generation is possible—this vastly simplifies the circuit design.

Values of τ_e are well known for a number of different media. In bulk semiconductors, τ_e is typically in the range 10^{-12} s to 10^{-10} s, and both measurements and theory have been reviewed in standard reference works [8], [9]. The much longer τ_e (10^{-7} to 10^{-6} s), which is found in bulk InSb and GaAs electron bolometric mixer devices, is due to a bottle neck for the energy relaxation process in these devices from the conduction band to the donor levels [1]. It is worthwhile to explore in some further depth why bulk semiconductors are limited to such a narrow bandwidth when used as hot electron mixers, and why no wider bandwidth devices have been developed during the last thirty years. The energy relaxation time which is typically calculated refers to energy transfer to the lattice from a hot electron distribution within the conduction band, as shown in Fig. 3. At temperatures higher than that which corresponds to the splitting between the donor levels and the conduction band (roughly 50–100 K), almost all donors become ionized, and the only energy relaxation processes which are relevant are those within the conduction band, which thus are quite fast. At the much lower temperatures, which are used in bulk InSb or GaAs mixers, the donor states are occupied, and the slower relaxation to these states dominates, as also shown in Fig. 3.

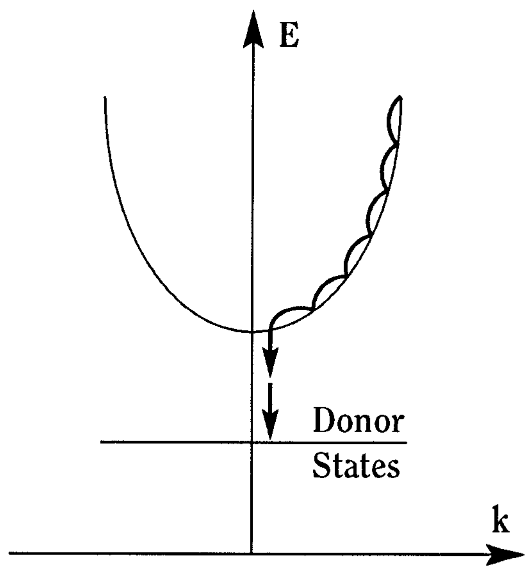

Fig. 3. Energy relaxation processes in a semiconductor.

For the 2DEG medium at an AlGaAs/GaAs interface, Sakaki *et al.* measured τ_e-values of 10^{-10} s to 10^{-9} s for temperatures below 10 K [10]. The shorter energy relaxation time compared with bulk GaAs at these temperatures apparently occurs because the donors and the electrons are well separated due to the modulation-doped structure of the material, hence energy relaxation within the band (actually sub-band(s)) dominates. There is thus a very real advantage to using the heterostructure configuration in this case, in that a much wider bandwidth should be feasible, as compared with bulk GaAs. At somewhat higher temperatures, 50 to 150 K, Shah found energy relaxation times of about 10^{-11} s to 10^{-10} s [11]. At these temperatures, Shah measured some lengthening of τ_e due to accumulation of optical phonons at the specific energy of about 36 meV (a so-called "hot phonon" effect). Due to this phenomenon, τ_e is shorter in material with a lower surface density of electrons, n_s, while at the lower temperatures the opposite dependence on n_s is obtained [10]. In both temperature ranges, the 2DEG medium should achieve bandwidths of the order of 1 GHz or greater, providing the solution for the longstanding problem of the narrow bandwidth of bulk semiconductor mixers. The 2DEG material systems have the further advantage that many different combinations of materials are feasible. They are the subject of an intensive research effort at present, so that considerable information is available on most aspects of physics and fabrication.

Recently, hot electrons have also been studied in thin films of superconductors [12], [13]. These studies have shown that the energy relaxation time for Nb is such that bandwidths of the order of 100 MHz are feasible, while wider bandwidths should be possible in NbN, as well as in YBCO. Intrinsic mixer conversion loss of close to 0 dB and bandwidth of 40 MHz were deduced from measurements at about 140 GHz [12].

A distinct mode of operation of superconducting film mixers is being pursued by Grossman *et al.*, [14]. This mode utilizes the nonlinear inductance of the film, rather than the resistance, and GHz bandwidths are anticipated.

Two-Dimensional versus Three-Dimensional Geometry

The original bulk hot electron mixer device consisted of a bar of InSb across a waveguide. The device impedance needs to be matched to the microwave circuit, and this can be accomplished by adjusting the length to cross-sectional area ratio, once the carrier concentration and mobility are given. The minimum size is determined by fabrication considerations, as well as the need to fit the device into the waveguide. Devices used in practise [1] contain close to 10^{10} electrons. In the 2DEG case, the device resistance (R_B) is

$$R_B = (L/W) * (1/en_s\mu) \quad (2)$$

Here, L and W are the length and width of the active region, n_s is the density in carriers per cm^2, and μ the mobility in cm^2/Vs. It is easy to adjust L/W by using photolithography, and a number of devices with the same resistance, which matches the microwave circuit, are possible. Specifically, the total number of electrons (N) in a typical device is smaller ($\approx 10^6$). The power required to drive the device nonlinear by heating the electrons is equal to this number times the energy loss rate (ELR) per electron. Although the ELR for 2DEG is greater than for InSb, corresponding to the shorter τ_e, the product of N and ELR is roughly the same, i.e., the two devices should require comparable LO powers at low temperatures (about 4 K). The Mode I mixer operates at a higher electron temperature, where the ELR is greater, and therefore needs higher LO power (≈ 1 mW).

Conversion Loss

The conversion loss expression for bulk semiconductor bolometric mixers was derived by Arams *et al.* [4]. We have extended their treatment to include some further effects, such as the finite reflection loss of a practical mixer ($T_0 = 1 - |\Gamma_0|^2$) [15]. The equivalent circuit of the device is shown in Fig. 4. When the conversion loss, L_c, is optimized with respect to the ratio $P_{\text{DC}}/P_{\text{LO}}$, one finds [15]:

$$\begin{aligned} L_c = {} & \frac{8}{T_o}\left(\frac{R_{Bo}}{CP_o}\right)^2 \left[\frac{(R_L + R_{Bo})^2}{4R_L R_{Bo}}\right] \\ & \cdot \left[1 - \frac{CP_o}{R_{Bo}}\left(\frac{R_L - R_{Bo}}{R_L + R_{Bo}}\right)\right] \\ & \cdot \{1 + (\omega_{\text{IF}}\tau_e)^2\} \end{aligned} \quad (3)$$

We have introduced R_{Bo}, which is the device resistance at an equivalent operating point for which the dc power is equal to the total dissipated power (P_o) at the mixer operating point, i.e., $P_o = T_o P_{\text{LO}} + P_{\text{DC}}$. Also, the factor C is defined as:

$$C = \frac{dR_B}{dP} \quad (4)$$

For our devices, C is almost independent of the bias current. R_L is the IF load impedance. The microwave circuit impedance Z_o, typically 100 ohms, is used to calculate T_o. The optimum value for L_c is 6 dB, which should be compared with 3 dB for a double-sideband Schottky-barrier diode mixer. SIS-mixers can have some conversion gain, and superconducting film bolometric mixers also indicate the possibility of conversion gain [12].

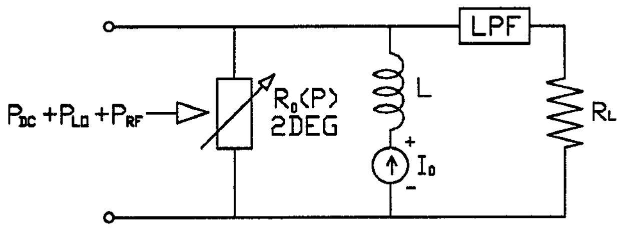

Fig. 4. Equivalent circuit of a hot electron mixer device.

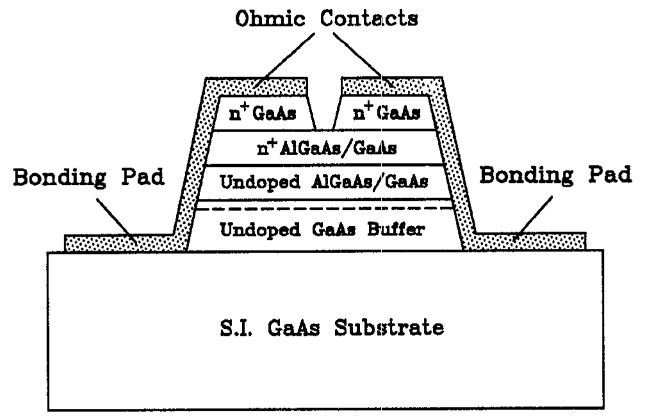

Fig. 5. Structure of the 2DEG device.

In order to compare calculated and measured conversion loss, one needs to perform a slightly different calculation than the one in (3), which assumes that the mixer has been optimized at all points of a curve of, say, L_c versus P_{LO}. An actual measured curve would represent L_c as a function of either P_{LO} or I_{DC}, with the other variable held constant. To perform this calculation, one finds it necessary to iteratively search for the correct operating point [15]. Data calculated using this method will be presented in the experimental section.

III. Materials Growth and Device Fabrication

2DEG Device Structure

A simple two-terminal device structure has been developed, which is shown in Fig. 5. The sequence of epitaxial layers is the same as is used for AlGaAs/GaAs HFET devices. Mesas are etched with a height of about 1.5 micrometers. The 2DEG sheet is then located within the mesa, which is surrounded by semi-insulating GaAs for isolation of the devices. The metalization of the devices consists of a standard sequence of evaporated layers for forming AuGe ohmic contacts, and the device pattern is defined by a lift-off process. Typically, gold plating is used for building up the metalization to sufficient thickness. There is a thin top layer of highly doped GaAs which facilitates the formation of good ohmic contacts. This layer has to be etched off after the devices have been defined. The wafer is finally thinned to about 125 micrometers, and a small chip cut out by first scribing the wafer. The I–V-characteristic is measured by probing the individual devices, which have sufficiently large contacts pads.

Materials Growth

The epitaxial layers are grown with low pressure MOCVD on undoped semi-insulating GaAs (100) substrates oriented 2 degrees off towards the (110) planes to achieve better morpology of the epi layers. The sources used are trimethylaluminum, trimethylgallium, 100% arsine, and silane as the n-type dopant. A typical device structure includes a 1 μm GaAs buffer, a 100 Å undoped AlGaAs spacer, 500 Å of uniformly doped AlGaAs, and a 200 Å doped GaAs contact layer. The Al content in the AlGaAs layers of early wafers was between 29% and 33%, and the dopant concentration in the high 10^{17} to 1×10^{18} range. Hall measurements were made on the as-grown layers using the van der Pauw technique at room, liquid nitrogen, and liquid helium temperatures. The best data obtained was a sheet charge density (n_s) of $1.3 \times 10^{12}\,\text{cm}^{-2}$ and a 77 K mobility of 95,000 cm^2/Vs. At 4.2 K n_s was the same, and the mobility 166,000 cm^2/Vs. As discussed in a later section, we also performed Shubnikov-de Haas measurements on a standard Hall bar configuration. These measurements showed un-equivocally that the samples contained 2DEG, and that the electrons were distributed in two sub-bands, with about 20% in the upper sub-band, and 80% in the lower one. DC heating tests determined a value for τ_e at low temperatures, consistent with the data given by Sakaki *et al.* [10]. More recently, improved material has been obtained ($n_s = 4.0 \times 10^{11}/\text{cm}^2$ and $\mu = 170\,000\,\text{cm}^2$/Vs at 77 K). We believe that the high sheet charge densities, with a relatively low-doped AlGaAs layer are a result of the high quality AlGaAs layers and interfaces, leading to very efficient transfer of electrons to the 2DEG channel.

We have also utilized material grown by MBE, courtesy of Dr. D. Massé, Raytheon Company, Lexington, MA. The maximum mobility of this material is quite similar to the early OMCVD material, as shown in Fig. 6. Both types of wafers were used to fabricate the devices tested in this work. We expect improved performance from the new OMCVD material.

I–V-Characteristic

The Mode I mixers were biased to the region indicated in Fig. 6, where it may be noted that the mobility is a strong function of lattice temperature in this region. It may be assumed that the mobility as a function of electron temperature follows essentially the same curve [11]. We may then conclude that the I–V-characteristic will tend to "saturate," as the electrons heat up when the voltage is increased. We show measured curves at low lattice temperatures for three different devices in Fig. 7. Dimensions and other data for the devices are given in the caption of this figure. The curves can be modeled with an analytical expression, which is useful in calculating data such as conversion loss:

$$I = \left(\frac{2I_o}{\pi}\right) \tan^{-1}(\alpha V) \tag{5}$$

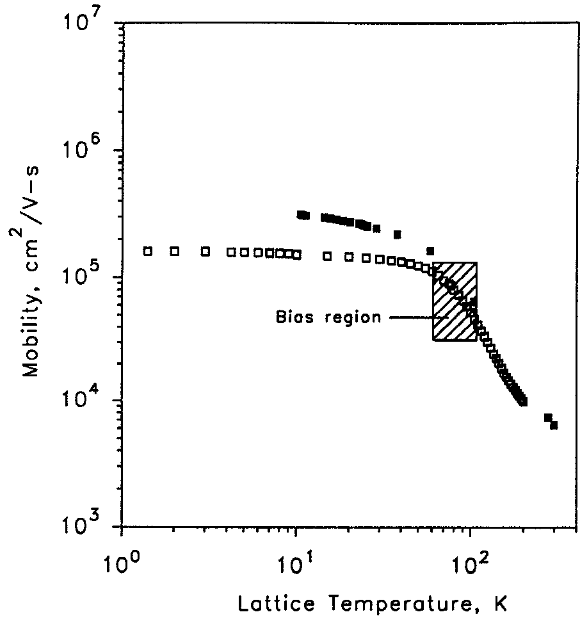

Fig. 6. Mobility versus lattice temperature for two 2DEG devices; □ = MBE Device. □ = MOCVD Device.

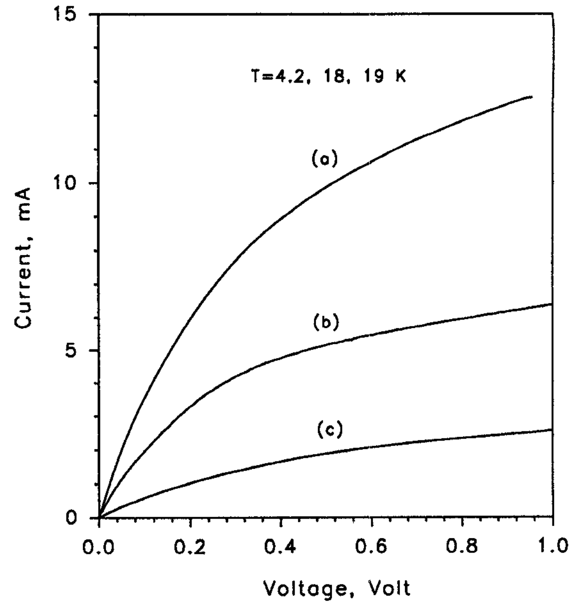

Fig. 7. Measured I–V-curves for three 2DEG devices; (a) MBE Device, $L = 6\,\mu\text{m}, W = 100\,\mu\text{m}, T_L = 4.2$ K; (b) MBE Device, $L = 5\,\mu\text{m}, W = 50\,\mu\text{m}, T_L = 19$ K; (c) MOCVD Device, $L = 43\,\mu\text{m}, W = 20\,\mu\text{m}, T_L = 18$ K.

IV. Experiments

Experimental Setup

Two different experimental setups were used: 1) A liquid helium dewar with built-in superconducting magnet. 2) A mechanical refrigerator which could provide temperatures to about 20 K. In both cases, the devices were mounted as flip-chips on a circuit etched on a Duroid 5880 substrate, which was inserted into a split-block mixer mount. The Duroid substrate is not ideal for low-temperature experiments, but was used for ease of fabrication and assembly. Improved mixer circuits on silicon substrates have been developed [16], and will be used in the future. RF and LO power were fed to the mixer through a stain-less steel waveguide, which was connected to the mixer block. The circuit inside the mixer block was essentially a finline transition, with the device soldered across the narrow part of the finline. One side of the finline had to be insulated, to allow the device to be biased. The IF was extracted from the device through a simple transition to a coaxial cable.

Measurements on the Mode I Mixer

The Mode I mixer was typically measured at about 20 K. The conversion loss is essentially independent of the lattice temperature over a wide range, up to about 100 K, so the exact temperature of operation is not important. The RF power (from a GUNN source) at the mixer block input was carefully calibrated with a power meter. The IF power was measured with a spectrum analyzer, which was also calibrated with a power meter. The measured numbers represent the conversion loss from the input of the block to the IF output connector near the block. As the LO, we either made use of another GUNN source, or (for higher power) a BWO.

The first measurement of the Mode I mixer was performed in the 4.2 K setup. It should be realized that the electron temperature is about the same, independent of the lattice temperature: we estimate a value of $T_e \approx 85 - 90$ K at the operating point. The conversion loss in the first measurement was 30 dB. The normalized response versus IF frequency is displayed in Fig. 8, which also shows the normalized response of InSb and GaAs bulk mixers as measured by others [1, 6]. It is clear that the 2DEG mixer provides a roughly three orders of magnitude increase in bandwidth compared with previous electron bolometric mixers. The 3 dB bandwidth is 1.7 GHz. Subsequent measurements at about 20 K have consistently shown the same bandwidth, but the minimum conversion loss has been improved to 18 dB.

The conversion loss has been calculated for two devices, with I–V-curves as shown in Fig. 7(a) ("4.2 K mixer") and 7(b) ("19 K mixer"), respectively. Fig. 9 shows the calculated conversion loss as a function of LO power (curves), compared with the measured data (points). The agreement is good, and indicates the validity of our theoretical approach. In Fig. 10, calculated and experimental data for L_c versus I_{DC} are compared. Again, the agreement is good, with a small shift of the current scale at low currents. The minimum conversion is well predicted. The increased conversion loss for the 19 K mixer at high bias currents may be due to lattice heating: the dissipated dc power at the highest current (10 mA) is about 200 mW! One general trend in comparing different devices, is that a device with low maximum (saturated) current requires less LO power to drive to optimum conversion loss. It is clearly also advantageous to have a high initial slope for the I–V-curve. The latter requirement can be satisfied by making the device wide, but this will lead to a larger saturation current. It is preferable to use a narrower device, and to maximize

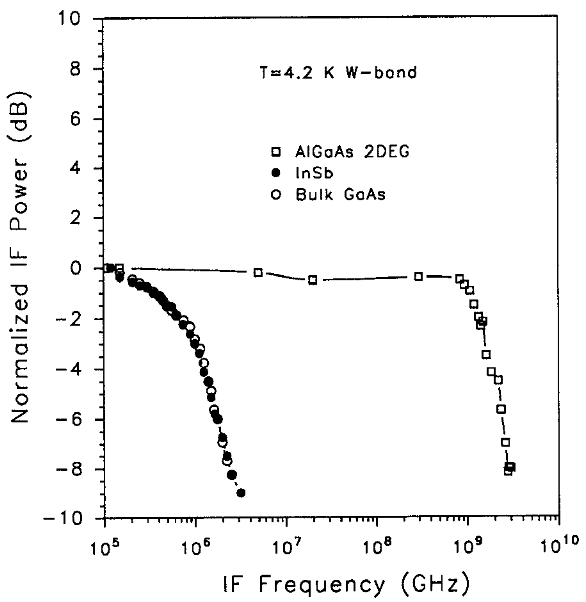

Fig. 8. Normalized IF response for the 2DEG mixer (Mode I), compared with InSb and GaAs bulk mixers [6].

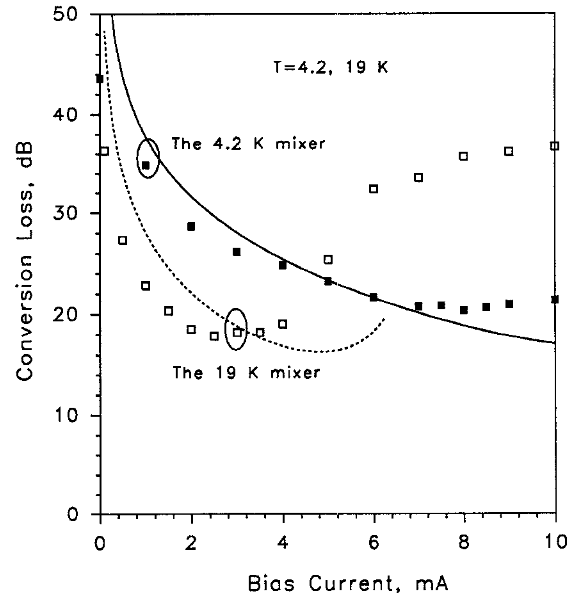

Fig. 10. Calculated and measured conversion loss for two 2DEG device (Mode I), versus dc bias current. LO power was 1.7 mW for the 4.2 K mixer, and 0.95 mW for the 19 K mixer.

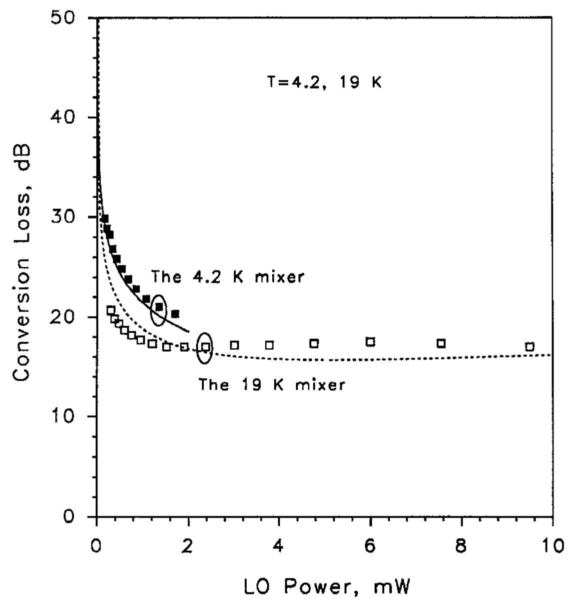

Fig. 9. Calculated and measured conversion loss for two 2DEG devices, versus LO power.

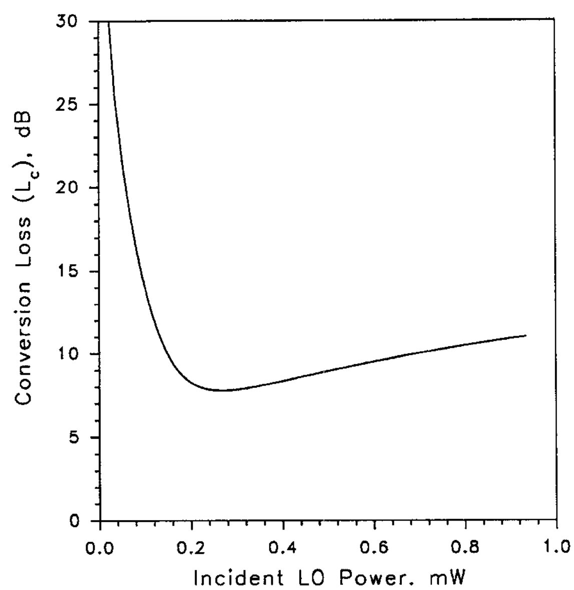

Fig. 11. Calculated conversion loss for an "optimum" next generation 2DEG device in Mode I.

the initial slope by choosing material with high mobility, as well as by keeping the contact resistance as low as possible. In the devices tested so far, the contact resistance appears to limit the value of the initial slope, and future improved devices are expected to yield considerably lower conversion loss. We have estimated a reasonable I–V-curve for a "next-generation" device, and calculated its optimum conversion loss, see Fig. 11. Note that both the conversion loss and the optimum LO power have been improved considerably.

Measured Results for the Mode II Device

As mentioned earlier, the Mode II device is expected to operate at about 4.2 K, and be biased by a magnetic field. We have demonstrated a Mode IIa detector at 94 GHz, similar to the one described by Smith, Cronin *et al.* [7], as shown in Fig. 12. The peak response occurs at the expected magnetic field for cyclotron resonance. The measured responsivity is about 0.5 V/W, which is much lower than obtained by Cronin's group (about 250 V/W) [17]. The reason for the lower responsivity is very much an open question at this stage; it is most likely due to differences in the materials used. We have measured a larger responsivity (5–10 V/W), at both 94 and 238 GHz, in a newly discovered mode (Mode IIb) at higher magnetic field, see Fig. 13. The device in this case was severely mismatched to the microwave circuit due to its very high resistance at high magnetic fields ($\approx 2\,k\Omega$). We can therefore estimate that the

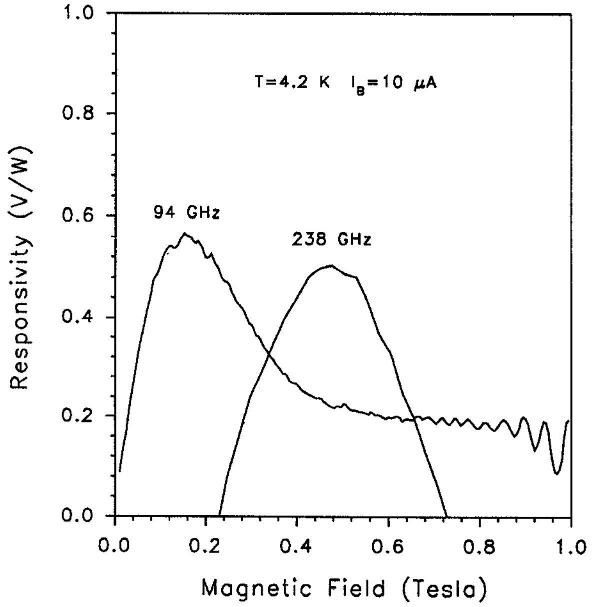

Fig. 12. Measured responsivity versus magnetic field for a Mode IIa 2DEG device operating as a direct detector at 94 GHz, and 238 GHz, respectively.

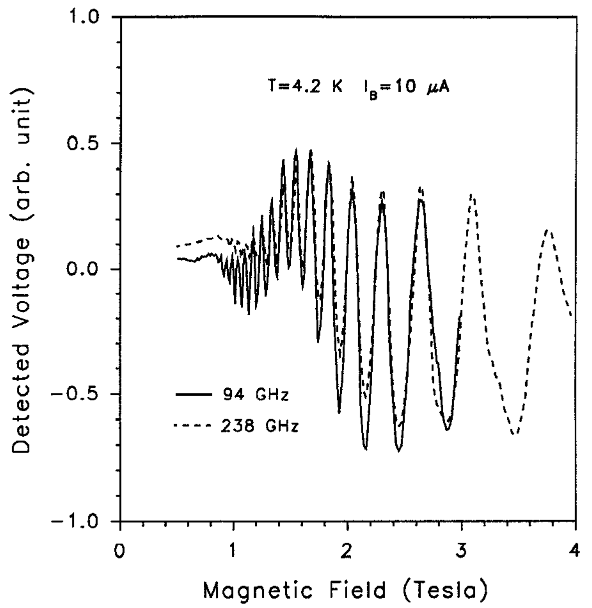

Fig. 13. Measured detected voltage output versus magnetic field from a Mode IIb 2DEG device, operating as a direct detector at 94 and 238 GHz, respectively.

responsivity in this mode may be increased to at least 50–100 V/W. The frequency independence of the responsivity up to 238 GHz is noteworthy. The detection mechanism is not yet known [15], but it is likely to involve transitions between (spatially) extended and confined states, which have been studied extensively in other work on the Shubnikov-deHaas and Quantum Hall effects.

We attempted to demonstrate mixing in both of the above Mode II devices, but were not successful in doing this. One indication that this negative result is not unexpected can be obtained by using the following expression for the optimum

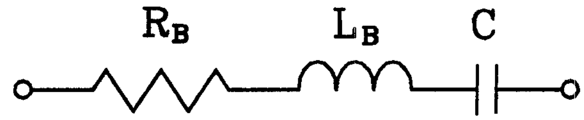

Fig. 14. Equivalent circuit of a 2DEG device, including a matching capacitor in series.

conversion loss, derived in [4]:

$$L_{\min} = 4\left[\frac{R_{Bo}}{CP_o}\right]^2\left[1+\sqrt{1-\left(\frac{CP_o}{R_{Bo}}\right)^2}\right] \tag{6}$$

where the quantity in the first set of square brackets can also be written:

$$\left[\frac{R_{Bo}}{CP_o}\right] = 1 + \frac{1}{I_o\mathcal{R}_o} \tag{7}$$

Here, $\mathcal{R}_o$ is the responsivity of the device as a detector at an equivalent bias current $I_o = \sqrt{P_o/R_{Bo}}$. For a responsivity of 10 V/W at a bias current of 10 μA, we predict $L_c \approx 86$ dB, which would not have been measurable. Further work on Mode II mixers then needs to emphasize attaining an increased responsivity in the detector mode.

V. Potential of Hot Electron Mixers for THz Frequencies

General Discussion

We have seen in the previous section that it is reasonable to assume that the conversion loss of the Mode I mixer may be decreased toward the 10 dB level. In order to estimate how these results at 94 GHz will scale with frequency, we must investigate how the absorption of the 2DEG varies with frequency. High mobility media, such as the 2DEG, have unusually long momentum relaxation times, τ_m. Such materials will show evidence of charge carrier inertia at lower frequencies than one expects for typical semiconductors. As can be shown on the basis of [18], [19], the equivalent circuit of the device (Fig. 14) will include an inductance, L_B, in series with the resistance, i.e.,

$$Z_B = R_B + j\omega L_B = R_o(1 + j\omega\tau_m) \tag{8}$$

where R_o is the low-frequency resistance. At an electron temperature of 90 K, representative of the operating points for 2DEG Mode I mixers, one may expect the $\omega\tau_m = 1$ point to occur at about 100 GHz, i.e., the inductive reactance is about 100 ohms at this frequency. Note that the inductance decreases as the dc bias and LO power are being applied and the electrons heat up. At higher frequencies, it will become necessary to resonate out this inductance by inserting a monolithic capacitor in series, as also shown in Fig. 14. Of course, other circuits may be used to match to the 2DEG device, such as a back-short in a waveguide, etc., but a monolithic circuit should yield the widest bandwidth. A different approach may be to find other material combinations which show the required nonlinearity, but with a lower maximum mobility, so that the reactance is minimized. We are pursuing microprobe measurements of 2DEG devices at frequencies up to 40 GHz and $T = 77$ K, in order to build up a base of information for designing matching circuits for 2DEG mixers at the higher frequencies [16]. These measurements have confirmed that the equivalent circuit contains a series inductance.

It was shown in the InSb case, that a Mode IIa type mixer [1] can conveniently be tuned to at least 1 THz, and suffer only a small increase in noise temperature. The effect of a large τ_m on a Mode IIa device is to narrow the cyclotron resonance linewidth. In this case, charge carrier inertia therefore does not limit the maximum frequency of operation. Our measured data also indicate a flat frequency response of the Mode IIb device.

Estimated Noise Temperature of Electron Bolometric Mixers

We may roughly estimate the expected noise temperature of a hot electron mixer by assuming that a conversion loss of 10 dB is achievable, and that the effective temperature of the device is equal to its electron temperature (≈100 K). This assumption is qualitatively consistent with the earlier data on InSb mixers. It amounts to regarding the device as a resistor at an elevated temperature equal to the electron temperature equal to T_e, and applying the Nyquist theorem. A cooled IF amplifier with a noise temperature of 10 K is also assumed. We then obtain:

$$(T_R)_{\mathrm{DSB}} \approx \frac{T_e}{2} \times (L_c - 2) + \frac{T_{\mathrm{IF}}}{2} \times L_c \approx 450\,\mathrm{K} \quad (9)$$

This receiver noise temperature would be competitive at frequencies in the 500 GHz to 1 THz range. Hot electron mixers which operate at lower electron temperatures would have a potential for even lower noise temperatures. This is one of the reasons for continuing to pursue the development of the Mode II mixers. It may be noted, though, that a mixer with $T_R = 450$ K at close to 1 THz, developed from the present 94 GHz prototype, may be a very good choice for space-based operation, since it only requires cooling to 50–80 K.

VI. Conclusion

For many years, bulk InSb electron bolometric mixers have been known to be capable of achieving very low noise temperatures, even up to frequencies close to 1 THz, but with only about 1 MHz bandwidth. In our work with a prototype 94 GHz 2DEG mixer, operating at 20 K, we have for the first time demonstrated an electron bolometric mixer with a bandwidth, which is sufficient for typical applications in the THz range. This type of mixer has the same advantages of low parasitics as the InSb version, but with added features such as potential for monolithic integration with the IF amplifier and antennas, etc. Further development should demonstrate the performance of this type of mixers at higher frequencies, and with lower conversion loss. Noise temperature measurements will be performed in the near future, which will enable us to make a firmer estimate of the noise temperatures which can be achieved at higher frequencies. Finally, we note that wide bandwidth electron bolometric mixers may be the general rule, not the exception, as one may have been tempted to think based on the earlier results achieved by InSb and GaAs bulk mixers. Many different 2DEG media exist, which could potentially be more optimum than the one we have started with. Further striking evidence is provided by the results with superconducting film hot electron mixers [12]–[14]. The evidence accumulated from these efforts supports the notion that the new electron bolometric mixers will find a niche of applications in the THz range.

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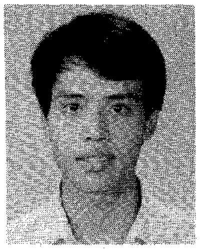

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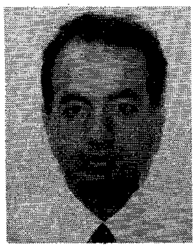

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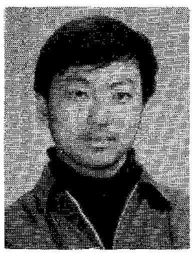

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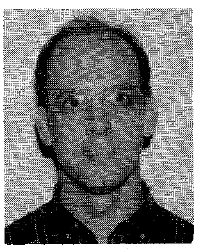

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