AlGaAs/GaAs Quasi-Bulk Effect Mixers: Analysis and Experiments

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ABSTRACT

The lowest noise temperature for any receiver in the 0.5 to 1 THz range has been achieved with the bulk InSb hot electron mixer, which unfortunately suffers from the problem of having a very narrow bandwidth (1-2 MHz) We have demonstrated a three order of magnitude improvement in the bandwidth of hot electron 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 20K, and calculations indicate that L_C can be decreased to about 10 dB in future devices. Calculated and measured curves of Lc versus PLO, and IDC, respectively, agree well. We argue that there are several different configurations of hot electron mixers, which will also show wide bandwidth, and that these devices are likely to become important as low-noise THz receivers in the future.

I. INTRODUCTION

In our contribution to the Second International Symposium on Space Terahertz Technology [1], we discussed the potential advantages of bulk and "quasi-bulk" (surface-oriented, or quasi-two-dimensional) mixer devices for the THz frequency range. A review of the receiver noise temperatures achieved in this range is given in Figure 1. This graph has been updated compared with the one in [1], using data given in presentations at the 1992 symposium. In the frequency range above 500 GHz, the lowest noise temperatures are still the ones reported for the InSb hot electron mixer [2]. Also, the frequency dependence of the receiver noise temperature of this mixer is much less steep than that for either the SIS or the Schottky diode mixers. We attribute these advantageous features 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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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 [3]. As originally pointed out by Smith et al.[4], it does not appear that this limitation should apply to all hot electron mixers, however, and our earlier paper [1] gave preliminary results which supported this idea. We demonstrated conversion with at least 1 GHz bandwidth in a mixer which employs a nonlinear element based on the two-dimensional electron gas (2DEG) medium at a heterojunction interface formed between AlGaAs and GaAs. Our continued investigation of this mixer at 94 GHz, reported in the present paper, has yielded a 1.7 GHz bandwidth, while the conversion loss has been improved from 30 dB to 18 dB. We have also obtained good agreement between measured and calculated conversion loss.

In this paper, we review the properties of hot electron mixers, especially those employing the 2DEG medium, and present our measured and calculated data. Two different modes of operation have been attempted: (1) Type I: This is the type of mixer which we have demonstrated. It operates at temperatures up to about 100K, and requires LO power of the order of a milliwatt. (2) Type II: The Type II mixer was proposed by Smith et al. [4], operates at about 4K, and requires the use of a moderately large magnetic field There are two distinct magnetically biased hot electron mixers: Type IIa is tuned to cyclotron resonance with the help of a fairly low magnetic field (< 1T). So far, this type of device has been demonstrated as a detector, but not as a mixer. The LO power is predicted to be in the microwatt range, or lower. We have also proposed a mixer (Type 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 so far been demonstrated.

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. The potential extension of two-dimensional hot electron mixers to THz frequencies is finally assessed.

II. FREQUENCY CONVERSION IN HOT ELECTRON MIXERS

Basic Mechanism

Hot electron mixers employ a nonlinear (electron) bolometer device of the type shown in Figure 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 As discussed in greater detail in [1], the basic nonlinearity which gives rise to mixing in hot electron mixers is associated with 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). A typical curve of $R_B = R_B(P)$ for a 2DEG device is shown in Figure 3.

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. The bandwidth of the mixer extends up to a frequency given by [1]:

$$B \approx 1/\,2\pi\,\tau_e \qquad (1)$$

Values of τ_e are wellknown for a number of different media. In bulk semiconductors, τ_e is typically in the range 10^{-12} to 10^{-10} seconds, and both measurements and theory have been reviewed in standard reference works [5,6]. The much longer τ_e (10^{-7} to 10^{-6} s), which is found in bulk InSb and GaAs hot electron mixer devices, is due to a bottle neck for the energy relaxation process in these devices from the conduction band to the donor levels [2]. 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 Figure 4. At temperatures higher than what corresponds to the splitting between the donor levels and the conduction band (roughly 50-100K), almost all donors become ionized, and the only energy relaxation processes which are relevant are those within the condcution 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 much slower relaxation to these states dominates, as also shown in Figure 4. A wide band mixer employing bulk GaAs may be designed at the higher temperatures, but does not appear to have been attempted. One reason may be that too much heating of the lattice occurs, see the discussion below which compares "three-dimensional" and "two-dimensional" devices.

For the 2DEG medium at an AlGaAs/GaAs interface, Sakaki et al measured τ_e-values of 10^{-10} to 10^{-9} s for temperatures below 10 K [7]. 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} to 10^{-10} s [8]. At these temperatures, Shah found evidence for 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 [7]. 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 [9,10]. 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.

A distinct mode of operation of a superconducting film mixers is being pursued by Grossman et al., see another paper at this conference. A range of materials and modes of operation for hot electron mixers with much improved bandwidth capability thus is now available. Only detailed future studies will show which of these materials that is optimum for a THz hot electron mixer.

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 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 [2] contain close to 10^{10} electrons. In the 2DEG case, the device resistance (R_B) is

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

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 in a typical device is smaller ($\approx 10^6$). Less power is then required to drive the device nonlinear by heating the electrons, since the power loss per electron at a given temperature is basically a materials constant. This fact probably explains why a bulk GaAs hot electron device at 50-100 K may be difficult to realize.

Conversion Loss

The conversion loss for bulk semiconductor mixers was derived by Arams et al. [11]. We have extended their treatment to include some further effects, such as the finite reflection loss of a practical mixer ($T_0 = 1 - |\Gamma_0|^2$) [12]. The equivalent circuit of the device is shown in Figure 5. When the conversion loss, L_c, is optimized with respect to the ratio P_{DC}/P_{LO}, as well as the IF load impedance, R_L, one finds [12] :

$$L_c = 8\left(\frac{R_{Bo}}{T_o C P_o}\right)^2 \left[\frac{(R_L+R_{Bo})^2}{4R_L R_{Bo}}\right] \left[1 - \frac{CP_o}{R_{Bo}}\left(\frac{R_L - R_{Bo}}{R_L + R_{Bo}}\right)\right] \left\{1 + (\omega_{IF}\tau_e)^2\right\} \qquad (3)$$

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. $P_o = P_{LO} + P_{DC}$. Also, the factor C is defined as (compare Figure 2):

$$C = dR/dP \qquad (4)$$

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.

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 [12]. 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 Figure 6. 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 then defined by a lift-off process. Typically, gold plating was 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 was finally thinned to about 125 micrometers, and a small chip cut out by first scribing the wafer. The IV-characteristic was 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 were trimethylaluminum, trimethylgallium, 100% arsine, and silane as the n-type dopant. Further details of the process can be found in our paper at the previous conference. We have also utilized material grown by MBE, courtesy of Dr. D. Masse', Raytheon Company, Lexington, MA. The maximum mobility for both types of materials is quite similar, as shown in Figure 7.

IV-Characteristics

The Type I mixers were biased to the region indicated in Figure 7, 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 [8]. We may then conclude that the IV-characteristic will tend to "saturate", as the electrons heat up when the voltage is increased. We show measured curves att low temperatures for three different devices in Figure 8. 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:

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

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 are under development [13], 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 Type I mixer

The Type 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 100K, 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 Type 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 $T_e \approx 85$ - 90K at the operating point. The conversion loss in the first measurement was 30 dB. The normalized response versus IF frequency is displayed in Figure 9, which also shows the normalized response of InSb and GaAs bulk mixers as measured by others [2,3]. It is clear that the 2DEG mixer provides a roughly three orders of magnitude increase in bandwidth compared with previous hot electron 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 IV-curves as shown in Figures 8(a) ("4.2K mixer") and 8(b) (19K mixer"), respectively. Figure 10 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 using our theoretical approach. In Figure 11, 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 loss is well predicted. The increased conversion loss for the 19K 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 IV-curve. The latter requirement can be satisfied by making the device wide, but this will lead to a larger saturation current. It si preferable to use a narrower device, and to maximize 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 devices are expected to yield considerably lower conversion loss. Another effect, which we have noticed, is that the initial resistance increases after the device has been soldered into the circuit. It is thus reasonable use the calculated conversion loss for the best device which we believe is feasible to fabricate, as an indication of the performance which should be feasible. The optimum conversion loss for such a "next generation" device is given in Figure 12. Note that both the conversion loss and the optimum LO power have been improved considerably.

Measured Results for the Type II Device

As mentioned earlier, the Type II device is expected to operate at about 4.2K, and be biased by a magnetic field. We have demonstrated a Type IIa detector at 94 GHz, similar to the one described by Smith, Cronin et al. [4], as shown in Figure 13. The peak response occurs at about the expected magnetic field for cyclotron resonance.The measured responsivity is about 1V/W, which is much lower than obtained by Cronin's group (about 250 V/W)[14]. The reason for the lower responsivity is very much an open question at this stage; it may, for example, be 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 (Type IIb) at higher magnetic field, see Figure 14. The device in this case was severely mismatched to the microwave circuit due to its very high resistance at high magnetic fields ($\approx 2k\Omega$). We can therefore estimate that the 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 also noteworthy. The detection mechanism is again not yet known [12], 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 Type 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 conversion loss, derived in [11]:

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

where the quantity in square brackets can also be written:

$$\left(\frac{R_{Bo}}{CP_o}\right) = 1 + \frac{1}{I_o \mathfrak{R}_o} \qquad (7)$$

Here, $\mathfrak{R}_o$ is the responsivity of the device as a detector at an equivalent bias current $I_o = \sqrt{\frac{P_o}{R_{Bo}}}$. 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 Type 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 Type 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. As discussed at the previous conference, high mobility (i.e. long momentum relaxation time, τ_m) media, such as the 2DEG, will show evidence of charge carrier inertia at lower frequencies than one expects for typical semiconductors. At the electron temperature of 90 K, representative of the operating points for 2DEG Type I mixers, one may expect the $\omega\tau_m = 1$ point to occur at about 100 GHz. The equivalent circuit of the device (see Figure 15) then incorporates an inductance with a reactance of close to 100 ohms. At higher frequencies, it will become necessary to resonate out this reactance by inserting a monolithic capacitor in series, as also shown in this figure. Of course, other circuits may be used to match to the 2DEG device, such as a back-short in a waveguide, etc, but 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 in order to build up a base of information for designing matching circuits for 2DEG mixers at the higher frequencies [13].

Estimated Noise Temperature of Hot Electron 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. A cooled IF amplifier with a noise temperature of 10K is also assumed. We then obtain:

$$T_R \approx L_c * T_e + (L_c-1) * T_{IF} \approx 1000K \quad (8)$$

This receiver noise temperature would be competitive at frequencies in the 500GHz to 1THz 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 Type II mixers. It may be noted, though, that even a mixer with $T_R = 1000K$ at close to 1THz, developed from the present 94 GHz prototype, may be a very good choice, since it may only require cooling to 50-80K.

VI. CONCLUSION

For many years, hot electron mixers have been known to be capable of achieving very low noise temperatures, even up to frequencies close to 1THz, but with only about 1 MHz bandwidth. In our work with a 94 GHz 2DEG hot electron mixer, operating at 20K, we have for the first time demonstrated a hot electron mixer with a bandwidth, which is sufficient for all typical applications in the THz range. This type of hot electron 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 eprformance 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 hot electron 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 [9,10]. A final tabulation compares different hot electron mixers, see Table 1. The evidence from these efforts supports the notion that the hot electron mixers will find a niche of applications in the THz range.

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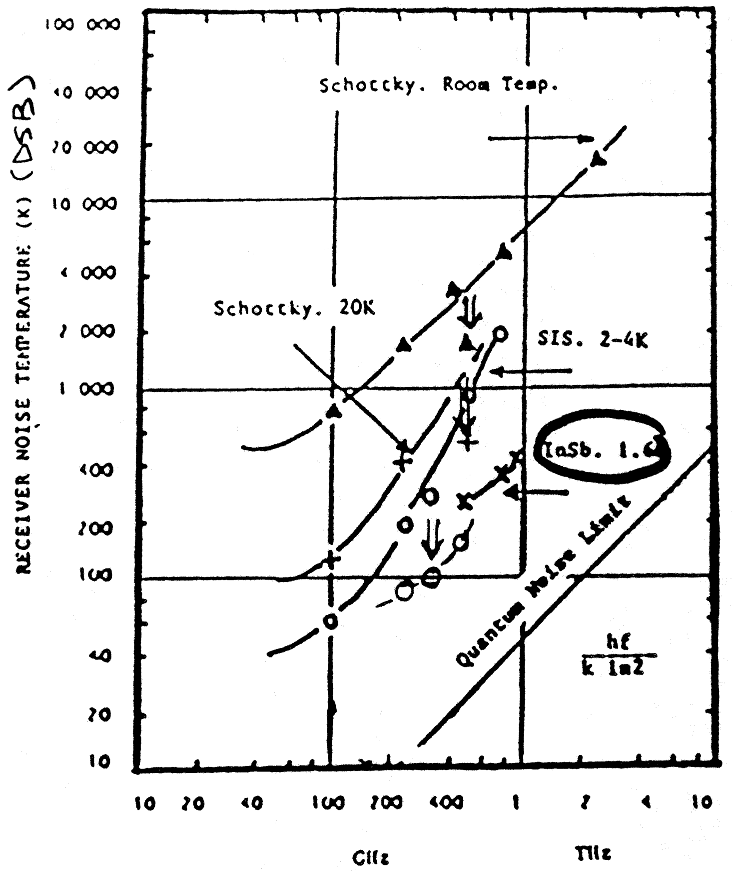

Figure 1. Receiver noise temperatures in the MM and Sub-MM range, versus frequency. The data for Schottky barrier diodes were originally compiled by E.L. Kollberg, and the SIS data by P.L. Richards. The InSb noise temperatures are from Brown et al. [2] .Some more recent data from this conference have been added (see arrows).

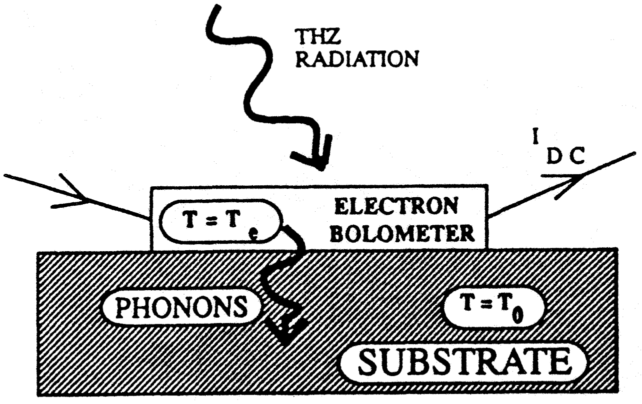

Figure 2. Schematic drawing of a generic electron bolometer device.

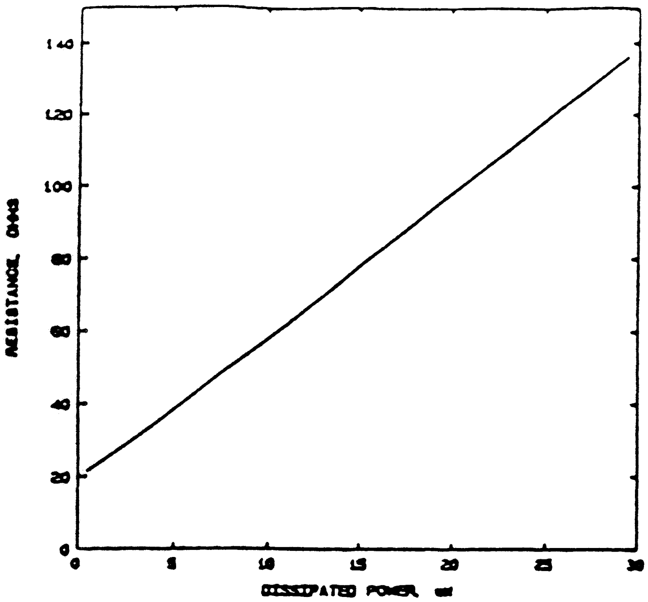

Figure 3. Typical curve of $R_B = R_B(P)$ for a 2DEG device.

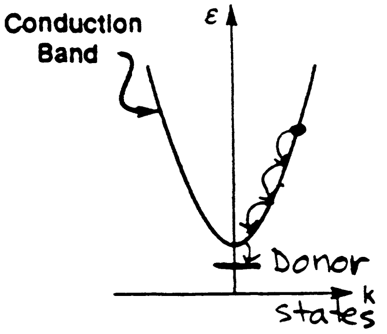

Figure 4. Energy relaxation proces in a semiconductor.

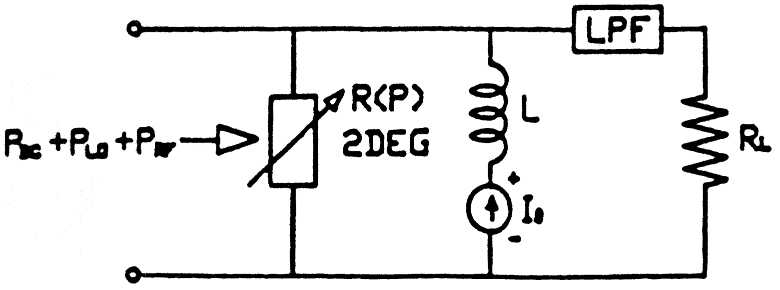

Figure 5. Equivalent circuit o a hot electron mixer device.

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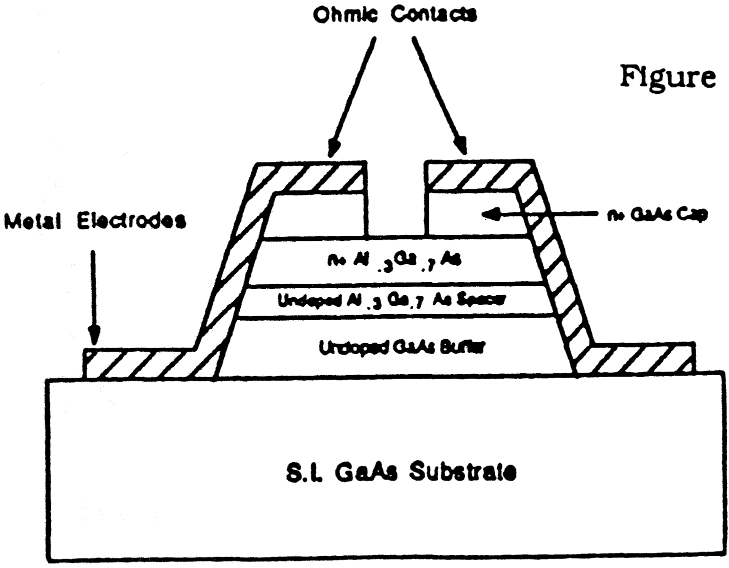

Figure 6. Structure of the 2DEG device.

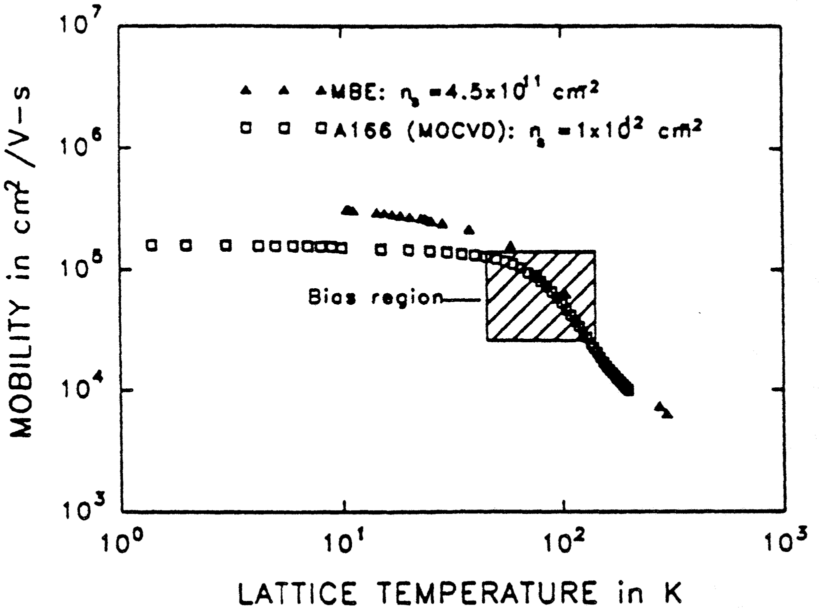

Figure 7. Mobility versus lattice temperature for two 2DEG devices.

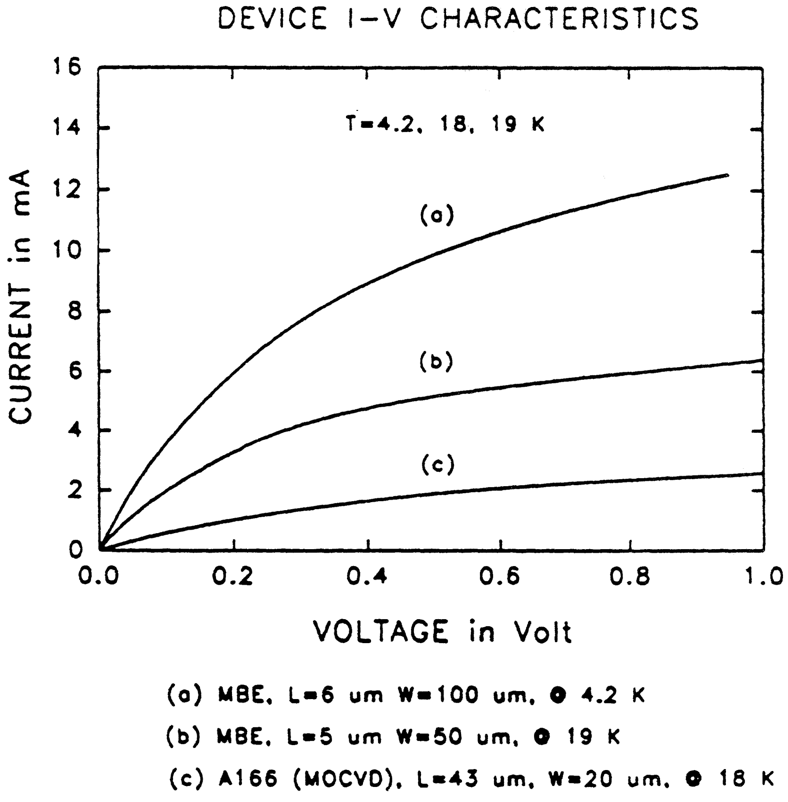

Figure 8. Measured IV-curves for three 2DEG devices.

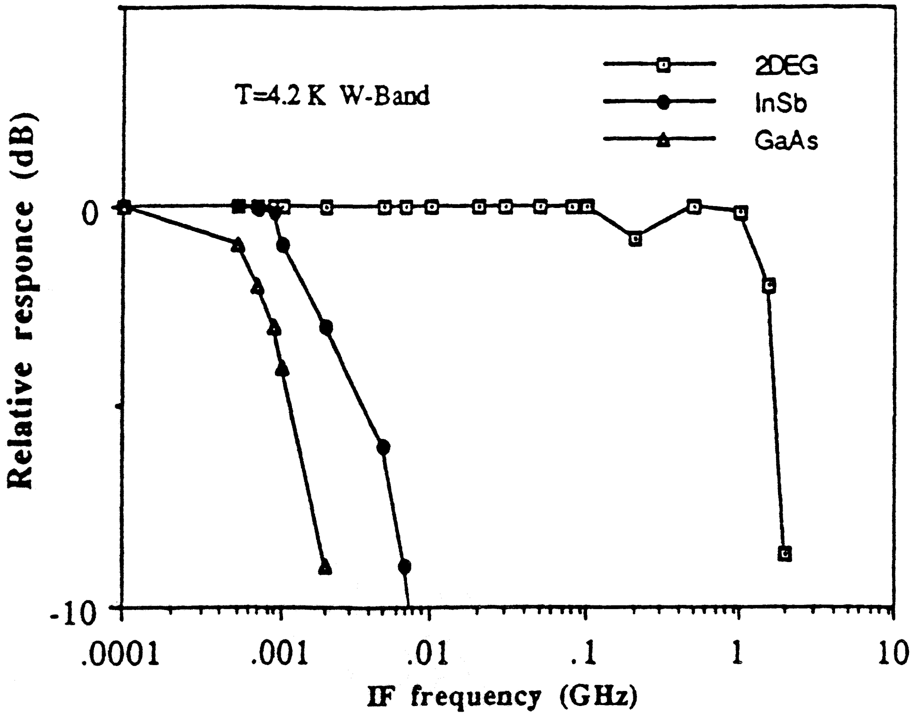

Figure 9. Normalized IF response for the 2DEG mixer, compared with InSb and GaAs bulk mixers.

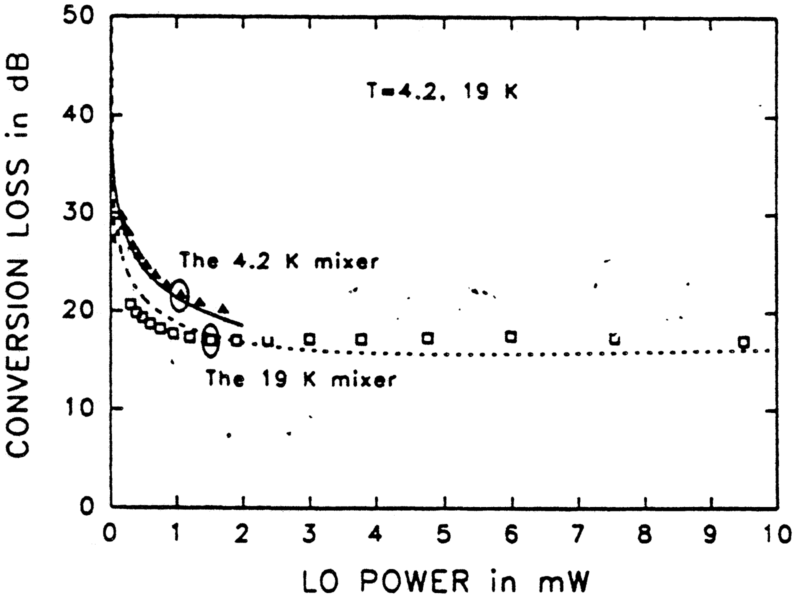

Figure 10. Calculated and measured conversion loss for two 2DEG devices, versus LO power.

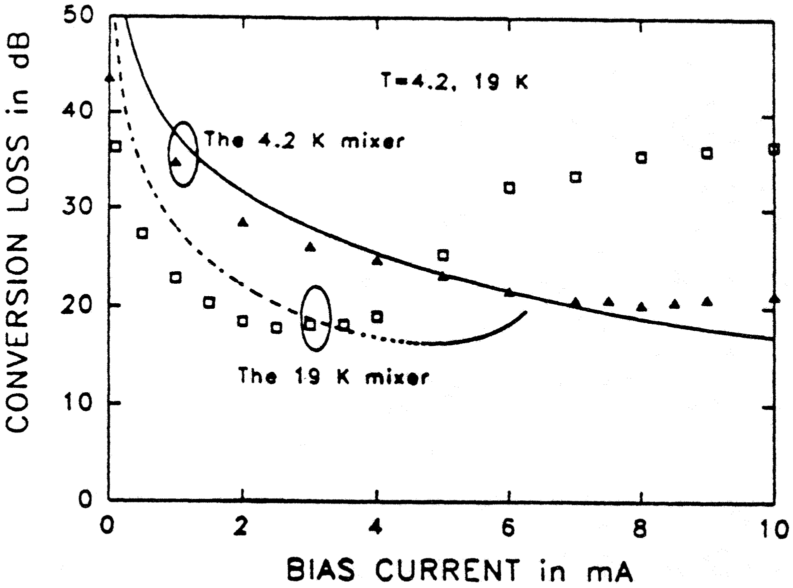

Figure 11. Calculated and measured conversion loss for two 2DEG devices, versus DC bias current.

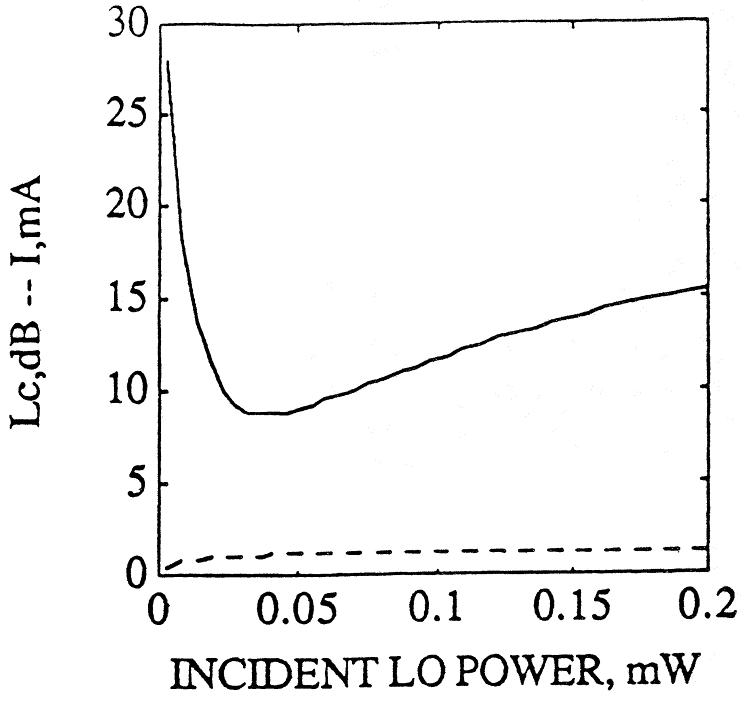

Figure 12. Calculated conversion loss for an "optimum" next generation 2DEG device.

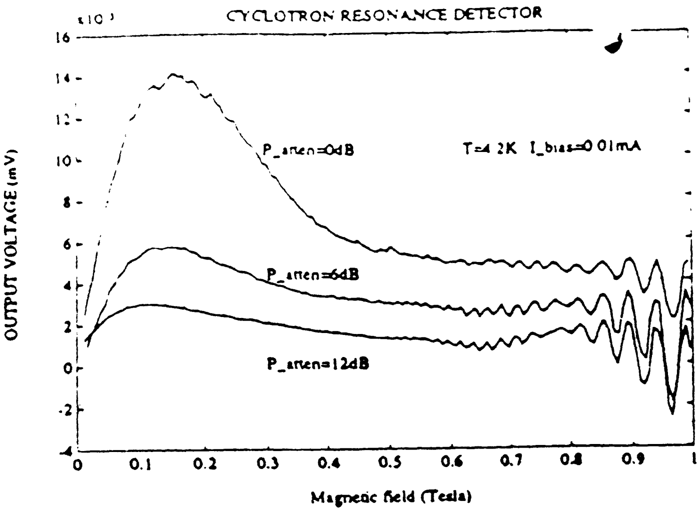

Figure 13. Detected voltage versus magnetic field for a Type IIa 2DEG device operating as a straight detector at 94 GHz.

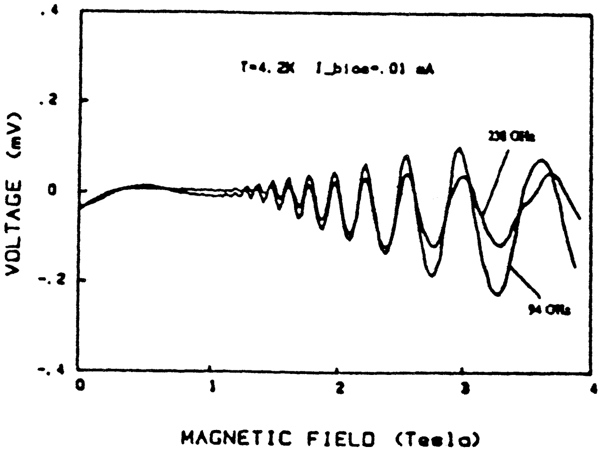

Figure 14. Measured detected voltage output versus magnetic field from a TypeIIb 2DEG device, operating as a straight detector at 94 and 238 GHz, respectively.

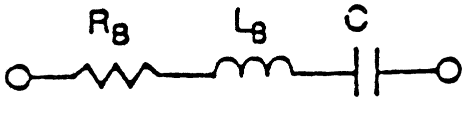

Figure 15. Equivalent circuit of a 2DEG device, including a matching capacitor in series.

COMPARISON OF DIFFERENT HOT ELECTRON MIXERS

MIXER TYPE		BAND-WIDTH	CONVERSION LOSS	T_R KELVIN
SEMI COND.	InSb	1 MHz	≈ 12 dB	300-500
SEMI COND.	2DEG 20/50 K	2 GHZ	18 dB (meas.) 10 dB (proj.)	1000 ?
SEMI COND.	2DEG 4.2K, MAGN. FIELD	1- 2 GHZ (proj.)	10- 13 dB (proj.)	300-500?
SUPER COND.	Nb (meas.)	100 MHZ	7.5 dB *	?
SUPER COND.	NbN (proj.)	Several GHz	? MIXING MEAS. AT 1.5 GHz **	?
SUPER COND.	YBCO (proj.)	Several GHz	12 dB (meas. at 2 GHz) ***	?
SUPER COND.	Nb, Nonl. Ind.**** (proj.)	200MHz -1GHz		70,000 @3THz Alloys lower

*) Gershenzon et al., IEEE Trans.Magnetics, MAG-27,1317 (1991) [9]

**) O. Vendik, Priv. Comm.

***) Kolesov, Chaloupka, et al., to be published, 1992

****) Grossman et al, this conf.