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ELECTRON BOLOMETRIC MIXERS FOR THE THZ REGION

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ABSTRACT

This paper reports new results related to 2DEG electron bolometric mixers for THz frequencies. We have measured the charge carrier inductance of a 2DEG device at 30 GHz, as well as the intrinsic device noise temperature at 1.5 GHz. 2DEG material with an increase in 4.2 K mobility by a factor of 3-4 has been grown by OMVPE. Detection by cyclotron resonance has been studied at 94 GHz and 238 GHz, with a maximum responsitivity (uncorrected for circuit loss) of 200V/W. Mixing has not been observed, so far, in this mode. The design principles for a 1 THz mixer are developed, and the DSB receiver noise temperature is predicted to be about 1000K.

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I. INTRODUCTION

In contributions to previous Space Terahertz Technology Symposia, we have discussed the potential advantages of bulk, or "quasi-bulk" (i.e. surface-oriented or quasi-two-dimensional) electron bolometric mixer devices for the THz range [1,2,3]. An updated graph of receiver noise temperatures for these frequencies is given in Figure 1. Above 500 GHz, the lowest noise temperatures are still the ones achieved with InSb bulk effect mixers in the mid 1980s [4]. The advantage of using the bulk configuration should become even greater as the frequency is increased further into the THz region, due to the very low parasitic reactance of a bulk device compared with junction devices such as the Schottky diode and the SIS device. Surface-oriented devices have further advantages compared with the InSb-type bulk configuration. These include ease of achieving a desired device impedance and size, as well as the feasibility of integration into monolithic circuits. We have also earlier demonstrated a roughly three orders-of-magnitude increase in the IF bandwidth (to 1.7 GHz) compared with the typical performance of InSb mixers, by using a surface-oriented medium: two-dimensional electron gas (2DEG), located at the hetero-junction between GaAs and AlGaAs [1,2,3]. It now appears that there are many different media and modes of operation which allow electron bolometric mixing [5], all with large IF bandwidth, as demonstrated in several other papers at this conference [6,7,8]. In the present paper, we will emphasize new results related to 2DEG electron bolometric mixers, and also discuss in some detail how a 2DEG mixer could be implemented in the THz range.

We need to introduce some nomenclature, in order to distinguish the different modes of operation of the 2DEG device:

(1) **Mode I.** This is a mode for which mixing has been demonstrated, with a preliminary minimum conversion loss of 18 dB, and bandwidth of 1.7 GHz, at an RF frequency of 94 GHz. The operating temperature is quite flexible, typically 20-77K, and the LO power required is about 1 mW.

(2) **Mode II.** The Mode II mixer was proposed by Smith et al.[9]. It operates at 4.2 K, and requires a moderately large magnetic field. There are two different versions of the Mode II 2DEG device: Mode IIa is tuned to cyclotron resonance with the help of a fairly low magnetic field ($< 2T$). Due to the lower operating temperature, one

predicts much lower LO power (nW-μW), and lower noise temperature. The cyclotron resonance tuning has been successfully used in InSb, and is a convenient method for reaching THz frequencies without experiencing problems with charge carrier inertia (discussed in some detail below). We describe some recent work on this mode in this paper. Mode IIb: This mode occurs in somewhat higher magnetic fields (1-5T), and appears to be connected with the Shubnikov-deHaas effect, which can be detected as oscillations of the DC resistance, when the magnetic field is varied. Detection of 94 GHz and 238 GHz radiation has been obtained in this mode, but no mixing so far.

II. MATERIALS GROWTH

2-DEG samples were grown in a horizontal low-pressure OMVPE system. The sources used were trimethylgallium (TMG), trimethylaluminum (TMA), 100% arsine and 50ppm silane diluted in hydrogen. The growth temperature was 700°C and the reactor pressure was 50 Torr. The V/III ratio was kept high (> 200) for better AlGaAs quality. The total gas flow was 4000 sccm. The estimated growth rate for GaAs and AlGaAs using these parameters were 5.5Å/s and 9 Å/s respectively. Typical 2-DEG structures include a 1.2μm GaAs buffer, a 360Å undoped AlGaAs spacer, a 500Å uniformly doped (mid-$10^{17}/cm^3$) AlGaAs, and a 130Å doped GaAs ($1 \times 10^{18}/cm^3$) contact layer. The Al composition in the AlGaAs layers is about 38%. The GaAs buffer was actually grown in two steps, 15 minutes at 650° C and then 20 minutes at 700° C. Initiation of the buffer at a lower temperature helps to preclude incorporation of impurities at the substrate and epilayer interface, which may create an undesirable parallel conduction path in the 2DEG device.

Although the maximum mobility we achieved (766,000 cm^2/V-s with 4.9×10^{11} electrons/ cm^2 at 2.2K after exposure to light) is still much lower than that obtained by MBE, to our knowledge, it is the highest by the OMVPE growth technique. Since the 2-DEGs are grown for device applications, light sensitiveness and overall thickness of the epi-layers are important considerations for device fabrication and testing. In addition to the requirement of high mobility, 2-DEG structures without the AlGaAs- related buffer are needed to minimize light sensitivity. To attain this goal, we found that deposition of AlGaAs in the reaction chamber prior to the growth of the 2-DEG structure provides a sufficient condition for producing a high mobility device. Samples grown with this type of reactor pre-conditioning have maximum light mobilities similar to those with AlGaAs-related buffers. More significantly, these devices are much less light sensitive, specifically, the dark mobilities are typically near 80% of the light values.

To compare the effectiveness of the pre-run and the conventional AlGaAs buffer technique, 2-DEG devices with either an undoped thick AlGaAs buffer or an AlGaAs/GaAs multiple quantum well buffer were grown. The parameters used for the 2-DEG structure were identical to those described earlier.

Characterization of the resulting 2-DEG structures was performed by computerized Hall effect measurement using the van der Pauw method. A plot of the Hall mobility versus temperature for the best sample is shown in Figure 2. Similar to other high-mobility 2-DEGs, the maximum mobility was measured at the lowest temperature, 2.2K. Without the pre-run or AlGaAs-related buffer, the maximum light μ_{77} obtained with optimized parameters ranges from 100,000 to 120,000 cm^2/V-s. Samples grown with pre-runs or with an AlGaAs-related buffer have increased light μ_{77} in the 140,000 - 170,000 cm^2/V-s range. We believe that the pre-runs leave a deposit of Al-rich compound in the reactor walls and the susceptor which effectively passivates the chamber and in subsequent experiments, helps to getter the impurities from the gas stream, allowing the growth of high purity GaAs and AlGaAs.

The most significant advantage of the samples grown with a pre-run is their reduced sensitivity to light, as evidenced by the dark to light mobility ratios shown in the table. The dark μ_{77} of these samples are typically about 80% of the light values, while the dark mobilities of samples with an AlGaAs or MQW buffer are only 50-60% of their light counterparts.

III. THE MODE I 2DEG MIXER

Measurement of the Charge Carrier Inertia Inductance

Charge carrier inertia was studied in bulk semiconductors at low temperatures in the 1960s [10]. It is not relevant under normal device conditions at room temperature, or when the electrons are accelerated substantially, unless one considers frequencies of the order of 500 GHz. In the 2DEG devices we have investigated, the electrons can have extremely high mobilities, and show charge carrier inertia phenomena at much lower frequencies. To make this quantitative, on can show [11] that to first order the effect is equivalent to an inductance, L_B, in series with the device resistance, R_B, see Figure 3. The total device impedance is:

$$Z_B = R_B + j\omega L_B = R_0(1 + j\omega\tau_m) \tag{1}$$

where R_0 is the low-frequency resistance. We have measured this inductance in a device for which the maximum electron mobility, μ, was about 90,000 cm^2/Vs at 77 K [12]. This mobility corresponds to a τ_m of

$$\tau_m = \frac{(\mu \times m^*)}{q} = 3.4 \times 10^{-12} s \tag{2}$$

Here, m^* is the effective mass $= 0.067m_0$, and q is the electron charge. The measured DC resistance was 27.1 ohms, and the microwave value $R_B = 20\Omega$. The measured resistance includes the contact resistance (R_p). As explained below, we believe that the contact resistance is largely eliminated at 30 GHz. This conclusion is consistent with a value for R_B at 30 GHz, which is less than the DC resistance. The corresponding inductance predicted from (1) and (2), and with R_B bracketed from 20Ω to 27.1Ω, thus is in the interval 0.068 to 0.092 nH. The measured value of L_B for the frequency range of 29 to 35 GHz was 0.08 $\pm$ 0.015 nH, which shows agreement with theory within the measurement error. We believe that this is the first measurement of charge carrier inertia in the 2DEG medium. We now describe how the measurement was performed.

A 2DEG device was flip-chip mounted with indium solder across a 50 ohm slot line of width 25 μm, etched in a thin copper layer deposited on a low-loss silicon substrate with thickness 0.33 mm. Cascade microprobe measurements were then performed after designing biasable coplanar waveguide (CPW) to slotline transitions [13] on the substrate, as shown in Figure 4. A network analyzer with an upper frequency limit of 40 GHz was utilized. Calibration standards etched on the same substrate allowed us to de-embed the device parameters, using the TRL ("thru-reflect-line") method. A room temperature measurement first determined the parasitic capacitance, C_p, of the device to 70 fF. Note that at room temperature the device inductance is negligibly small, since τ_m is about an order of magnitude shorter in this case. The parasitic inductance (L_p in Figure 3) was very small.

The substrate was next placed on top of a copper cylinder, which was surrounded by a liquid nitrogen bath, and the entire assembly substituted for the steel cylinder normally used to support substrates in the microprober. The measured and modeled response are compared in Figure 5, for three bias currents. As the bias current is increased, the inductance/resistance ratio decreases rapidly (see (1)), when the electrons begin to heat up. The inductance can then not be measured accurately at these frequencies, and future refinements in the measurement setup will have to be made to allow modeling of the device under conditions of substantial electron heating. It is clear that L_B/R_B decreases with increasing bias, however, which is the expected behavior.

Measurement of Intrinsic Device Noise

To assess the expected noise temperature of a THz mixer receiver, one can measure the device noise temperature at the IF frequency, as a DC bias current is applied. This method has previously been used for Schottky barrier diodes [14]. We have measured the available output noise temperature (T_d) from a 2DEG device connected to a CPW circuit on a silicon substrate, as a function of bias current. The device was cooled to 77K by immersion in liquid nitrogen. We corrected for the mismatch between the device and the 50Ω circuit by measuring S_{11} at the device terminals. The result is shown in Figure 6, which also gives the DC I-V-curve of the device. The noise was measured at 1.5 GHz. For a typical mixer bias point, T_d is about 100K. Note that this is close to the estimated electron temperature of 85-100 K. In future experiments, we will investigate the dependence of T_d on the physical temperature of the device, as well as on other device parameters, and the frequency at which T_d is measured.

Design of a Mode I THz 2DEG Mixer

Several design features will have to be revised in an actual THz 2DEG mixer design. The flip-chip mounting yields a much too high parallel capacitance, even if the chip is thinned considerably, as shown by the microprobe measurements. This capacitance basically disappears if the device is fabricated as an integral part of a monolithic circuit, made from semi-insulating GaAs. Coupling of the RF and LO is also best accomplished quasi-optically. Figure 7 shows two possible integrated antennas which may be used: (a) A tapered slot antenna, etched on a silicon-oxynitride membrane [15], and (b) an extended hyper-hemispherical dielectric lens [16]. If a silicon lens is used for alternative (b), then a good dielectric match is obtained to a GaAs substrate, clamped to the back of the lens.

The low power output of THz LO sources makes it important to minimize the LO power required. The 2DEG device can be scaled down in size while maintaining a constant impedance, if both width and length are scaled by the same factor. The main factor to watch is the contact resistance, which is inversely proportional to the device width, and thus will increase. In a typical device, the vertical distance from the contact pad to the 2DEG is 0.1 μm or less, and with the pad size of about $100 \times 100\mu$m used presently, there is then a capacitance shunting the contact resistance of about 11 pF. At 100 GHz, the capacitive reactance is 0.1 ohms, much smaller than the typical contact resistance, R_c, of 10-20 ohms. This circumstance allows us to design a 1 THz device with considerably smaller area, without problems with the contact resistance. R_c does have an effect at the IF frequency, but since the optimum IF impedance is several hundred ohms, a higher R_c can be tolerated in the IF circuit. Based on a smaller device size, with a width of 10 micrometers, we estimate that LO powers in the range 10-100 μW are feasible.

Another important factor to consider is the effect of the charge carrier inertia at 1 THz. In order to estimate this, we must know the effective value for $< \tau_m >$, under conditions of electron heating. It is convenient to introduce the frequency, f_m, at which $R_B = L_B$ (see (1)). Unfortunately, the detailed physics of the heated 2DEG medium is anything but simple. From a Monte Carlo simulation of 2DEG under similar conditions to those in our mixer, we can estimate $f_m = 500$ GHz. We have used values of f_m of 300 and 500 GHz, respectively, to predict the degradation in conversion loss, assuming a simplified equivalent circuit based on (1), i.e. an inductance in series with the resistance, see Figure 8. The conclusion is that a conversion loss from about 11.5 dB to 13 dB is predicted at 1 THz, when the conversion loss at 100 GHz is 10 dB. The predicted conversion loss at 1 THz is about in the same range as for Schottky barrier mixers: therefore the comparison of the two types of mixers depends critically upon the effective noise temperature of the respective devices. We may also note that at higher frequencies than about 1 THz, one may obtain a conversion loss which is close to that at the lowest frequencies by adding a monolithic capacitor in series with the device, and thus resonate out the effect of the charge carrier inertia inductance.

We can now proceed to an estimate of the receiver noise temperature of a Mode I hot electron mixer at 1 THz. We assume that the effective device temperature is roughly equal to the measured device noise temperature (T_d) at the IF, i.e. 100 K. With an IF amplifier noise temperature, T_{IF}, of 10 K, and $L_c = 13$ dB, we find

$$T_{R,DSB} = \left(\frac{T_d}{2}\right) \times (L_c - 2) + \frac{(T_{IF} \times L_c)}{2} = 1000K \tag{3}$$

This receiver noise temperature is about $15 \times (hf/k\ell n2))$ and would represent a significant advance in the state-of-the-art at THz frequencies. Major advantages of the 2DEG hot electron mixer, are the moderate cooling requirement (20–77K), and the completely monolithic fabrication technology.

IV. THE MODE IIa 2DEG MIXER (CYCLOTRON RESONANCE MODE)

Basic Requirements for Mode IIa

Cyclotron resonance is observable at frequencies high enough that the following conditions are fulfilled:

$$\hbar\omega_c >> kT \tag{4a}$$

and

$$\omega_c \times \tau_c > 1 \tag{4b}$$

where

$$\omega_c = eB/m^* \tag{4c}$$

is the cyclotron resonance frequency (B is the magnetic flux density). The relaxation time, τ_c, is often taken to be the same as the momentum relaxation time, τ_m, which can be derived from the mobility, and was discussed above in connection with charge carrier inertia. The scattering processes of the electrons in a magnetic field are often quite different from the case of drift in a uniform electric field, so τ_m should only be regarded as a first approximation for the value of τ_c in (4b). It is clear from the above conditions that in order

Table 1.1

Data for wafers used to study cyclotron resonance detection.

Wafer	77K		4.2K	
	$N_S(\times 10^{11})$	$\mu(cm^2/Vs)$ (light)	$N_S(\times 10^{11})$	$\mu(cm^2/Vs)$ (light)
TDEG 33 (OMVPE)	4.7	171,000	4.95	728,400
T7591 (MBE,IBM)	4.5	173,240	4.23	790,610
G587(MBE, ref.[9])	5.2	202,000	5.6	1,410,000
G585(MBE,ref.[9])	2.4	205,000	3.35	2,410,000

to observe cyclotron resonance (CR) one requires a combination of (1) a low temperature (2) a high frequency, and (3) a high mobility. The 2 DEG medium is ideal for detecting CR at reasonably low frequencies, since μ is quite high at low temperatures. One can detect CR either in absorption, or by a photoconductive effect. Smith, Cronin et al [9] showed that the 2DEG medium has a strong CR photoconductive effect at frequencies from 94 GHz to 3 THz. They employed samples with mobilities as high as 2.4×10^6 cm^2/Vs, and estimated that the maximum detector responsivity was at least 300 V/W. In order to further investigate this effect, we are performing a comparative study of 2DEG samples from different sources, including some of the samples used in [9]. The mobility at 4.2 K ranges from about 200,000 cm^2/Vs to 2.4×10^6 cm^2/Vs. The main characteristics of representative wafers are summarized in Table 1.

Experimental Results

Although the study is still ongoing, some preliminary results are very interesting, and are mentioned here. We are using a system as shown in Figure 9. A typical device configuration is as shown in Figure 10.

(1) The responsivity at 94 GHz ranges from 1 V/W for the lowest μ sample, as previously reported in [2], to over 100 V/W for the IBM sample with $\mu = 790,000$ cm^2/Vs. If mismatch losses are accounted for, we find a maximum responsivity close to 135 V/W. The responsivity at 238 GHz is higher than at 94 GHz by at least a factor of two. The responsivity saturates as the microwave power is increased, as shown in Figure 11.

(2) The linewidth measured at 238 GHz is much narrower than at 94 GHz (typically by a factor of two). Two typical recordings are given in Figure 12 (for the IBM wafer) . The linewidth also appears substantially narrower than that predicted from accepted theories (0.02T for the highest mobility device).

One can use the responsivity of the straight detector to predict mixer performance, if it is assumed that the hot electron bolometer theory of Arams et al. [17] applies. The approximate minimum conversion loss is:

$$(L_C)_{\min} \simeq 4\left(\frac{1}{\mathcal{R}I_o}\right)^2$$

where $\mathcal{R}$ is the responsivity of the device as a detector, and I_o the bias current. With currently demonstrated responsivities, we predict a conversion loss of $\sim$ 50 dB. Experiments are under way to investigate this second mode of mixing. We can potentially increase $\mathcal{R}$, which would decrease L_C to values of practical use. The expected noise temperature in this mode, if successful, should be considerably less than for the Mode I mixer. LO power should be 1 μW or less, and the bandwidth a few hundred MHz.

V. CONCLUSION

We have explored the requirements on a THz 2DEG mixer by measuring charge carrier inertia and intrinsic device noise, and by developing improved 2DEG material. The new data enable us to predict the performance of a THz 2DEG mixer with greater confidence, and a receiver noise temperature of about $15\times$ $(hf/k\ell n2)$ or less appears feasible. We have also obtained preliminary results in the cyclotron resonance mode, with strong detected signals. Further experiments are needed to determine whether mixing is possible in this mode.

VI. ACKNOWLEDGEMENTS

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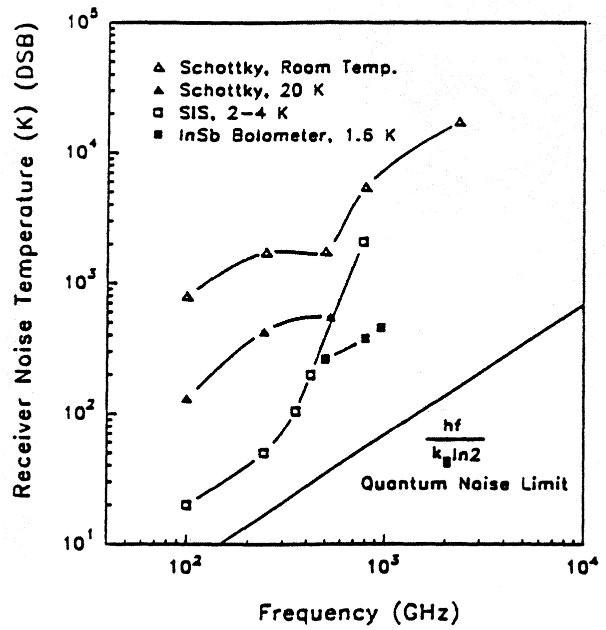

Figure 1. Receiver noise temperatures in the millimeter and submillimeter wave frequency ranges.

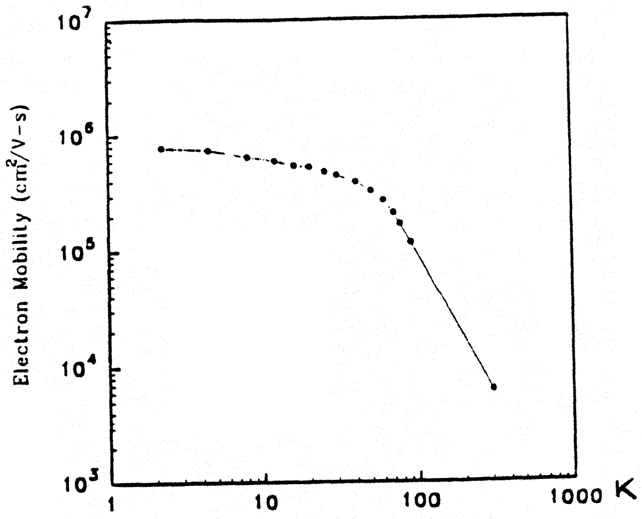

Figure 2. Mobility versus temperature for the best wafer grown by OMCVD.

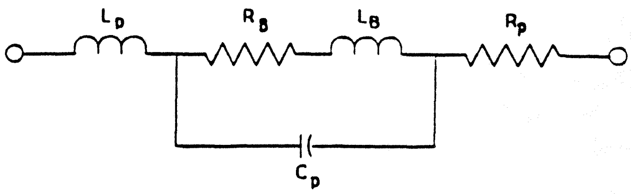

Figure 3. Equivalent circuit of the 2DEG device, including the effect of charge cárrier inertia.

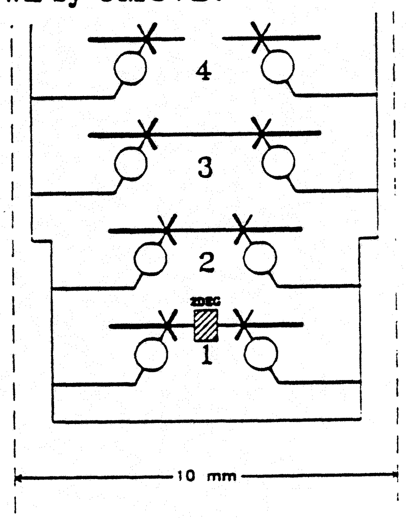

Figure 4. Back-to-back coplanar waveguide to slotline transitions, used to Cascade probe a 2DEG device.

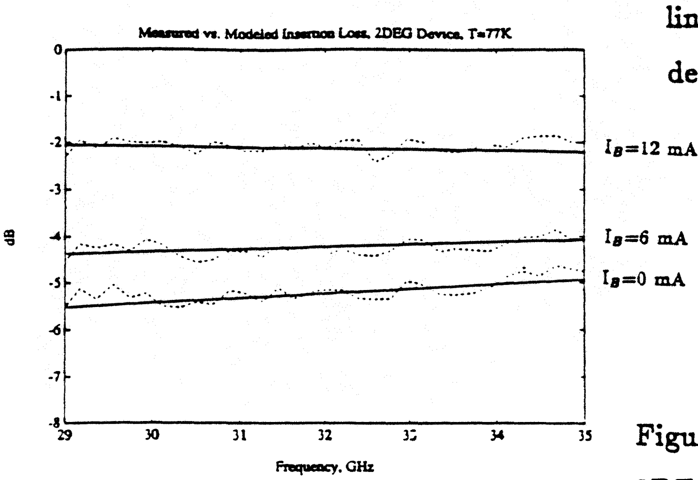

Figure 5. Measured and modeled response of a 2DEG device at 77 K, for three different bias currents.

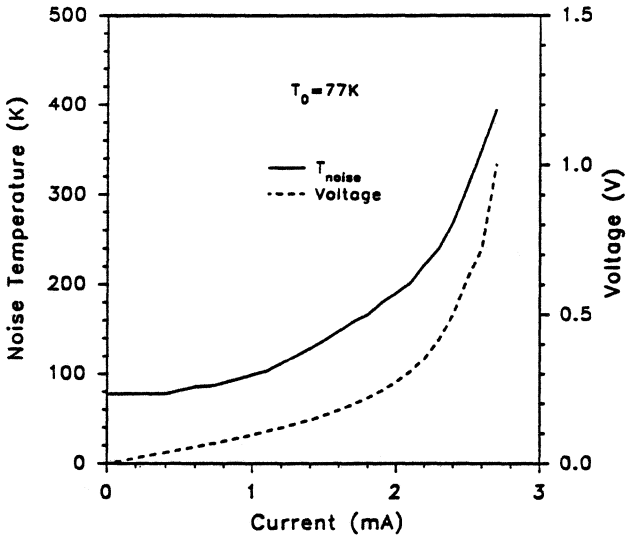

Figure 6. Measured device noise temperature at 1.5 GHz versus bias current. The DC I-V-curve is also shown.

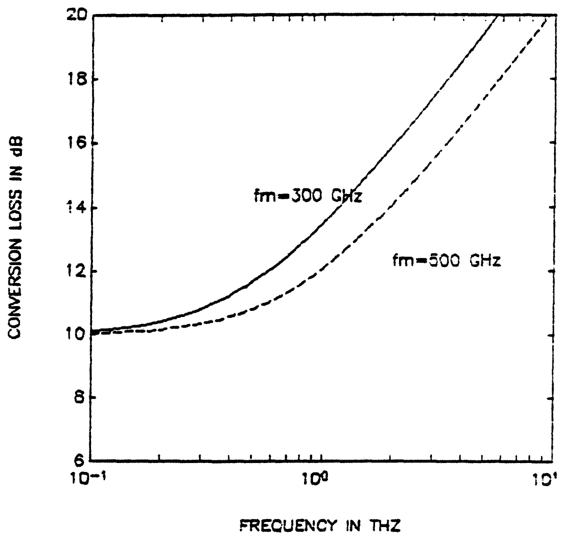

Figure 8. Predicted increase of the conversion loss of a 2DEG mixer in the THz range.

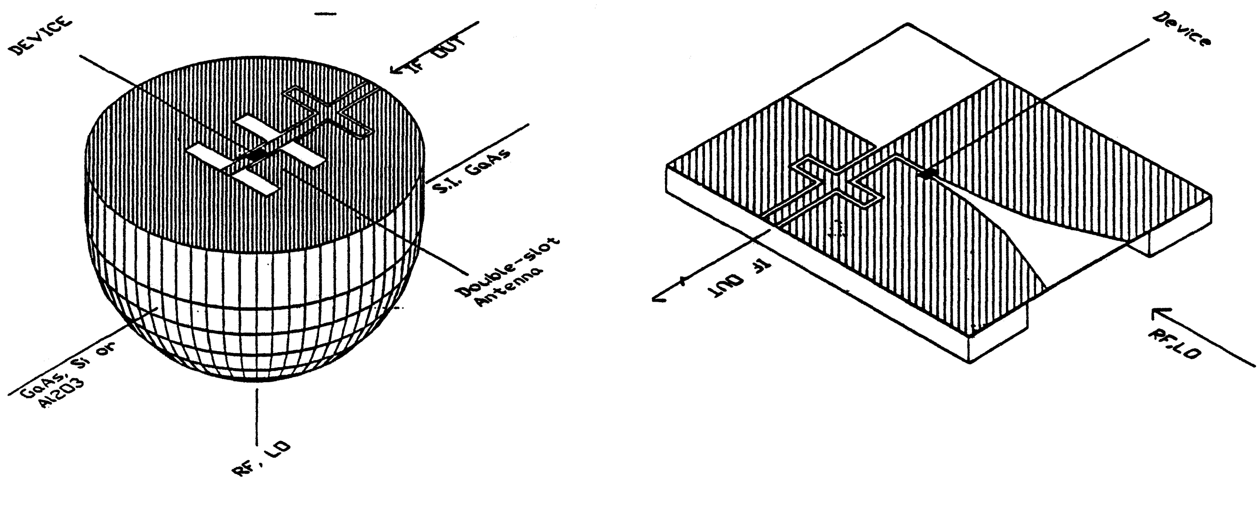

Figure 7. Integrated circuit antennas which could be used with a THz 2DEG device.

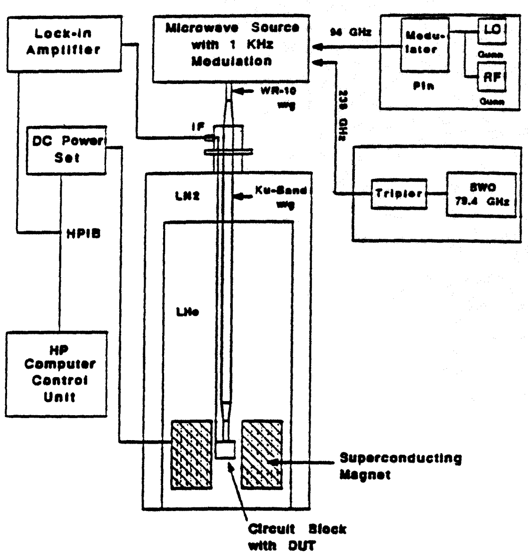

Figure 9. The system used to measure the cyclotron resonance photoconductive effect.

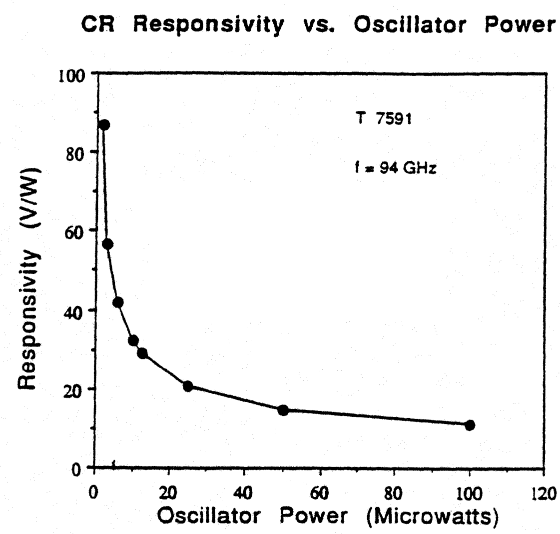

Figure 11. Responsivity versus microwave power for a device made from the IBM wafer (T7591).

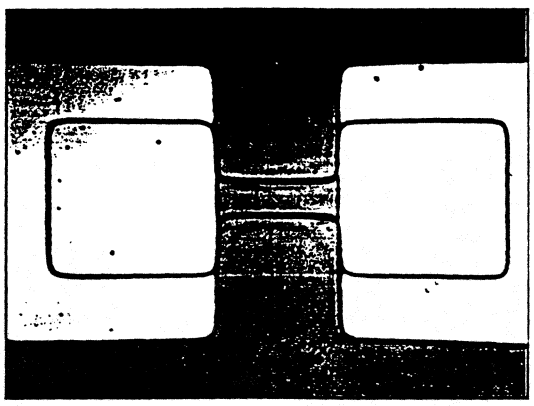

Figure 10. Typical device configuration used in the CR experiments.

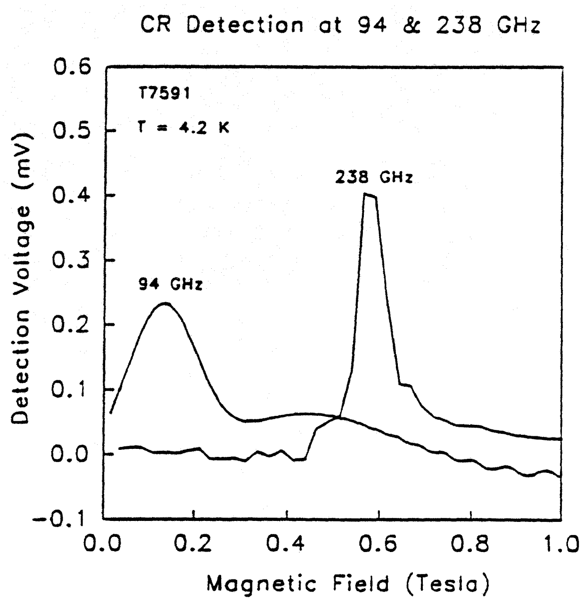

Figure 12. Recordings of CR at 94 and 238 GHz, respectively, for the same device as in Figure 11. The input power was about $5\mu W$ at both frequencies, and bias current $30\mu A$.