CYCLOTRON RESONANCE DETECTORS FOR THz FREQUENCIES

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ABSTRACT

Cyclotron resonance (CR) detectors, employing the two-dimensional electron gas (2DEG) medium at the hetero-interface between AlGaAs and GaAs, have been demonstrated from 94 GHz (3.2 mm wavelength) to 2.4 THz (119 μm wavelength). Both MBE material and in-house OMVPE grown material were tested. Responsivity as high as 5,000 V/W was measured at 1.8 THz, with an estimated detector NEP about 3.3×10^{-12} W/$\sqrt{\text{Hz}}$. In addition to the CR response, strong detection due to a Shubnikov-de Haas like effect was also demonstrated. Detection of fast laser pulses at 600 GHz (496 μm) and 1.2 THz (256 μm) at cyclotron resonance, showed that the time-constant of the detector is ≤ 4 ns. The time-constant when the Shubnikov-de Haas effect is employed is somewhat slower, of the order of 12-15 ns.

I. INTRODUCTION

Applications such as astronomy, remote sensing, and laboratory experiments with pulsed laser sources, require a sensitive and fast detector for frequencies from 0.5 THz to several THz. Typical direct detectors are too slow for these tasks. One of the most sensitive detectors in the submillimeter region is the InSb hot electron bolometer. This device relies on the heating of electrons, and the subsequent change of the resistance, for detection. The InSb device can be tuned in frequency by using a magnetic field, and the peak response then occurs at the frequency for cyclotron resonance [1]. It can be used both in the direct detection mode and in the heterodyne mode. As a direct detector, it has high responsivity and a response time of about 10^{-7} seconds. It has also been operated as a heterodyne detector up to 2.4 THz. A similar detector using the two-dimensional electron gas (2DEG) medium was proposed by Smith et al. [2]. We have investigated the 2DEG cyclotron resonance detector over a wide frequency range (94 and 238 GHz, as well as 1.0, 1.8, and 2.4 THz), employing the 2DEG formed at a heterojunction between AlGaAs and GaAs. The 2DEG CR detector is projected to have a response time from 10^{-10} to 10^{-9} seconds, and thus be considerably faster than earlier detectors of this type. Smith et al. also proposed a heterodyne detector based on the 2DEG device. The potential bandwidth is predicted to be from 0.2 GHz to 2 GHz, and the 2DEG device also has the potential for very low noise. This paper briefly reports the experimental results of our current research on millimeter and submillimeter detection using 2DEG devices.

II. DEVICE FABRICATION

The 2DEG devices were fabricated on $Al_xGa_{1-x}As/GaAs$ epi-layers grown on semi-insulated GaAs wafers by MBE and OMVPE. The detector geometry at millimeter waves is a simple bar between two contact pads with a typical size of $200\mu m \times 50\mu m$, as shown in Figure 1. The nonlinear 2DEG element consists of a planar sheet of 2DEG, formed at the interface between AlGaAs and GaAs, similar to the medium used in HEMTs, but without the gate. At THz frequencies, two types of square detector configurations, with overall size of 1mm × 1mm were designed (Figure 2). One has an open faced structure, and the other has an interdigitated contact structure. The interdigitated contact structure has six fingers total; the space between the fingers is 180 μm, and the width of a finger is 40 μm.

In order to successfully demonstrate the cyclotron resonance detection/mixing effect, the mobility of the device should be high, and the sheet charge density should be $\sim 3 - 4 \times 10^{11}$ cm^{-2}. It may also require a unique combination of materials parameters. In our detector experiments, the 2DEG devices are fabricated on several high mobility samples grown both by MBE and OMVPE. The mobilities of these samples are as high as 2×10^6cm^2/V-sec, and the sheet charge densities are in the low 10^{11} cm^{-2} range, at 4.2K. The material parameters of these samples are listed in Table 1.

Table 1: 2DEG Material Parameters

Material	77 K		4.2 K	
	N_s ($\times 10^{11}$ cm^{-2})	μ (cm^2/V-s)	N_s ($\times 10^{11}$ cm^{-2})	μ (cm^2/V-s)
TDEG33(OMVPE)	4.7	171,000	4.95	728,400
T 7591 (MBE)	4.5	173,240	4.23	790,610
G 587 (MBE)	5.2	202,000	3.64	1,410,000
G 585 (MBE)	2.4	205,000	3.35	2,410,000

In our 2DEG device fabrication processing, wet chemical etching is used for device isolation. The height of the mesa is about 1.5 μm. The 2DEG sheet is then located within the mesa, which is surrounded by semi-insulating GaAs for isolation of the device. The metallization 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. In order to reduce the millimeter wave loss due to the dielectric reflection, the millimeter wave devices are thinned down to 5 mil.

III. EXPERIMENTAL RESULTS

A. Detection of CW Radiation

The experimental system at UMass/Amherst for the 2DEG CR detector measurements is shown in Figure 3. A liquid helium dewar with a superconducting magnet provides cooling to 4.2 K and a magnetic field of up to 5 Tesla. Different millimeter wave and submillimeter wave sources are used: (1) for 94 GHz and 238 GHz, we employ a Gunn oscillator, and a BWO with a varactor tripler, respectively, fed through an oversize waveguide; (2) at the THz frequencies, we use the 163μm (1.8 THz), and 119μm (2.4 THz) lines of a CO_2-laser pumped molecular laser, guided to the sample through light pipes. At 94 and 238 GHz, the detector device is mounted as flip-chips on a printed circuit on a 5 mil quartz substrate, which is inserted into a waveguide block. For the THz experiment, the detector is placed in an integrating cavity.

We have investigated a number of high-mobility samples grown by MBE (μ_{4K} up to 2.4×10^6 cm^2/V-s) and OMVPE (μ_{4K} up to 7.4×10^5 cm^2/V-s) at the frequencies mentioned above. The responsivity at 1.8 THz is as high as 5,000 V/W (Figure 4), much higher than at 94 or 238 GHz (100-200 V/W) (Figure 5). The characteristics of the detector can be very different for devices fabricated from different wafers, indicating the complicated scattering processes occurring in the 2DEG medium biased with a magnetic field. The device configuration also plays an important role in the detector performance. In general, the open-faced devices show a single CR line only, whereas the interdigitated devices also show a detected pattern which is periodic as a function of inverse magnetic field (1/B), see Figure 6. The latter effect is similar to the Shubnikov-de Haas oscillations which can be seen in the resistance of the device, also shown in Figure 6. Our experimental results are summarized in Figure 7, showing the approximate detector responsivity versus frequency. To find the responsivity, we measured the output power of the laser, and also estimated the loss of the light pipe. Our superconducting magnet was limited to a maximum field of 5 Tesla; therefore we could not reach the cyclotron resonance field at 2.4 THz. Instead, we were able to demonstrate detection due to a Shubnikov-de Haas like effect at this frequency (Figure 8).

The samples with the highest responsivity (R) at 1.8 THz were grown by MBE, and have mobilities of about 790,000 cm^2/V-s. An OMVPE grown sample with similar mobility yielded R=600 V/W at 1.8 THz. These responsivities are much higher than those previously measured for this type of detector [2]. Further increase of R is possible by using lens coupling to a small detector.

B. Detection of Pulsed Radiation

This investigation was started with the motivation of developing a sensitive THz detector with fast response. We have performed a preliminary test which shows that the CR/2DEG detector is about two orders of magnitude faster than the InSb detector. We employed a pulsed laser system at the Submillimeter Technology Laboratory, University of Massachusetts/Lowell. A TEA CO_2 laser was used to pump a cavity-dumped THz gas laser with NH_3 as the active medium. The cavity-dumping was accomplished by directing a Q-switched pulse from a frequency-doubled YAG laser at a silicon etalon inside the THz laser cavity. A THz pulse with a FWHM of about 7 ns and peak power 100-200 W was created by this system (see the diagram in Figure 9). A Schottky diode detector in a corner-cube mount served as a comparison detector, which was assumed to be fast enough so as not to distort the THz pulse.

The laser was tuned to two different frequencies: (1) 1.2 THz (256 μm), and (2) 600 GHz (496 μm). The cyclotron resonance fields were 2.9 Tesla and 1.5 Tesla for these two frequencies. The detectors were grown by MBE, and had mobilities of 790,000 cm^2/V-s and 1,410,000 cm^2/V-s, respectively. Both samples gave pulse-widths of about 12-15 ns at the higher frequency, substantially broadening the pulse detected by the Schottky-diode (FWHM = 7 ns, see Figure 10). The width of the CR-detected pulse was essentially independent of the bias current, up to 600 μA. At the lower frequency, the CR detector produced a pulse only slightly broader than the Schottky-detector, see Figure 11. A CR detector time-constant of 4 ns is consistent with the data. This time is an upper limit, since the pulses from the CR detector may have been further lengthened by circuit effects, compared with the Schottky detector. These effects will be investigated further. The fastest response was found for larger bias currents, with a constant pulse width being observed from 150 μA to 5.7 mA. Tuning the magnetic field to 2.9 Tesla, and still using the 600 GHz line, we found a much longer pulse-width of about 15 ns. We believe that this detection is due to the Shubnikov-de Haas (SdH) effect. One should note that the SdH detections are located at specific magnetic fields, periodic in 1/B (compare Figure 6), and that these positions are independent of the laser frequency. Since the cyclotron resonance field for 1.2 THz was also 2.9 Tesla, there must have been a coincidence between the CR field and the SdH field in the 1.2 THz measurements. This could explain why the time constant was so much slower at 1.2 THz. We tentatively conclude, then, that the time-constant for CR detection in the 2DEG medium is $\leq$ 4 ns, while the SdH effect time-constant is of the order of 12-15 ns.

IV. DISCUSSION AND CONCLUSIONS

A. Mechanism of Detection

Detectors of millimeter waves/submillimeter waves which utilize cyclotron resonance in a 2DEG have been explored in a number of earlier papers [3-7]. Most of this work has been aimed at understanding the physics of the 2DEG medium in a magnetic field, and only mentions the possibility of developing a detector as an aside. The quoted responsivity has often been quite low (about 1 V/W), and the response time has usually not been measured. It is not clear from most of these experiments how the responsivity and the NEP vary with parameters such as mobility, detector configuration, bias current, or frequency of the detected radiation.

Thiele et al.[8] used a thin gate to control the density of the 2DEG, and to pick up a detected, photo-voltaic response. A voltage is induced on the gate, as the Fermi energy in the 2DEG changes abruptly on passage through a Landau level. To interpret the shape of the cyclotron resonance response versus magnetic field, one must introduce an inhomogeneous electron density, which gives rise to states in between the Landau levels. The inhomogeneity of the electron density is likely to be related to a non-uniform distribution of the ionized impurities (donors) in the AlGaAs and in the quantum well. Non-uniform distribution of the donors is likely to be important in our devices as well.

The responsivity of Thiele et al's detector appears to be about 25 V/W. A radiation-induced increase in electron temperature by about 10 K was deduced.

Dieβel et al.[9] introduced a different principle for detection, i.e. scattering of the electrons between edge states is promoted by the absorption of the submillimeter waves. This scattering is made possible by introducing two gates which deplete the electron gas over part of the width of the detector. The sub-mm-induced scattering then occurs between the two gates. This detector operated at 1.2 K, and a responsivity of close to 10,000 V/W was estimated. The optimum bias current was only about 100 nA.

Our own experiments show that comparable responsivity to that obtained by Dieβel et al. can be obtained in a much simpler detector configuration. Also, the response time has now been measured for the first time. The following major experimental conclusions were obtained:

(1) The optimum responsivity obtained so far increases by one to two orders of magnitude as the frequency of the detected radiation goes from 100-200 GHz to 1.8 THz.

(2) As the electron mobility varies from 200,000 to about 10^6 cm^2/V-s, the responsivity at 100-200 GHz increases from about 1V/W to 200 V/W. The optimum mobility for 1.8 THz detection is close to 10^6 cm^2/V-s. The optimum electron density is likely to be the one which results in the maximum mobility, i.e. 3-4 $\times 10^{11}$ cm^{-2}.

(3) Due to incomplete data, we can not determine if the highest mobility sample ($\mu =$ 2.4 $\times 10^6$ cm^2/V-s) yields the highest responsivity.

(4) "Shubnikov-de Haas type" detection occurs, with somewhat lower responsivity, but only in the interdigitated devices.

(5) For the CR mode, we find a response time of $\leq$ 4 ns while the SdH effect detection is considerably slower, about 12-15 ns.

From (1), we deduce that the Landau levels have to be well separated in order for the detection mechanism to work optimally. At 94 and 238 GHz, this is not the case, judging from the measured cyclotron resonance linewidths.

From (2), we can see that the samples with optimum responsivity in general are those with high mobility. High mobility is known to be related to low impurity concentration in and near the channel; also, the remote impurities in the AlGaAs separated from the channel by a fairly thick (400 Å) spacer. This rule is not universal, however, indicating that the exact nature and location of the impurities can influence the mobility and the detector responsivity differently. An example of this effect is that detectors fabricated on OMVPE and MBE wafers with similar mobility and density yielded quite different responsivity results.

A very tentative explanation of our results can be formulated as follows: Due to local fluctuations in the potential related to the distribution of impurities, a given Landau level will fluctuate through the device, in relation to the Fermi level. At least in the interdigitated devices, conducting channels may form across the detector when the local energy is equal to the Fermi energy (or higher), as indicated by Büttiker [10]. At energies well separated from the Fermi energy, only localized states are possible, similar to the inter-Landau level states discussed by Thiele et al.[8]. An increase in the electron temperature, caused by absorption of submillimeter wave radiation, will change the number of channels which are able to percolate across the entire detector. It is not clear if this mechanism is feasible in the open-face detectors, since these are about 1×1 mm in size. Adiabatic electron transport has been observed in edge channels in long, narrow geometries over distances of 200-400 μm [10]. Future investigation will have to further clarify these tentative ideas about the detection mechanism in cyclotron resonance detectors.

Whether the above tentative explanation is correct or not, it is likely that hot electron phenomena are involved. We then expect the time-constant to be of the order of the energy relaxation time, τ_e. This relaxation time is known to be close to 1 ns from Shubnikov-de Haas measurements [11], which is consistent with the upper limit of 4 ns estimated from our pulse measurements. It is also noteworthy that the detector operated well even with a bias as high as 5.7 mA. At this bias, the electron temperature can be estimated to be in the range 50-80 K [5], an unusually high temperature for observing the CR effect.

B. Design of a Heterodyne Detector

By analogy with the InSb hot electron detector, we expect that the 2DEG detector will also operate in the heterodyne mode. The measured response time (τ) indicates that the heterodyne version should have a minimum IF bandwidth equal to $1/2\pi\tau =$ 50 MHz based on our pulse measurements. Further measurements of actual mixing are needed to confirm what the bandwidth will be under optimum heterodyne detector conditions, which may be different from those in the pulse experiments. The device output noise temperature is expected to be of the order of the electron temperature (15 K), with a possible extra term due to electron temperature fluctuations (compare to the superconducting mixer case, see [12]). With a conversion loss similar to what is obtained for InSb mixers (10-13 dB), we then predict a DSB receiver noise temperature of roughly 100-200 K. Judging from our direct detector results, it will be difficult to obtain low conversion loss in the millimeter wave range; this is an experiment which must be attempted in the actual THz range. Initially, it may be useful to employ the same "open" optical coupling method which we have used for the direct detectors. However, a more optimum solution would be to couple via an extended hemi-spherical lens, as shown in Figure 12. Further development is ongoing to realize a lower resistance detector element, which can be matched to the antenna element behind the lens. Typical antenna elements can be a log-periodic spiral, or a double-dipole or double-slot antenna. These present an impedance of 50-100 ohms, whereas the present version of the detector has a typical resistance of 1.5 kohms, due to the magneto-resistive effect. The responsivity in the straight detector case will increase in inverse proportion to the linear size of the device: It is thus possible to reach responsivities of the order of 10^5 V/W, and NEPs of 10^{-13} to 10^{-14} W/$\sqrt{\mathrm{Hz}}$.

ACKNOWLEDGMENTS

This work was supported by NSF under grant ECS-9208752. The authors would like to thank Dr. N. Cronin of University of Bath, UK, for providing MBE samples for this work. Technical assistance by F. Agahi and R. Basco is also acknowledged.

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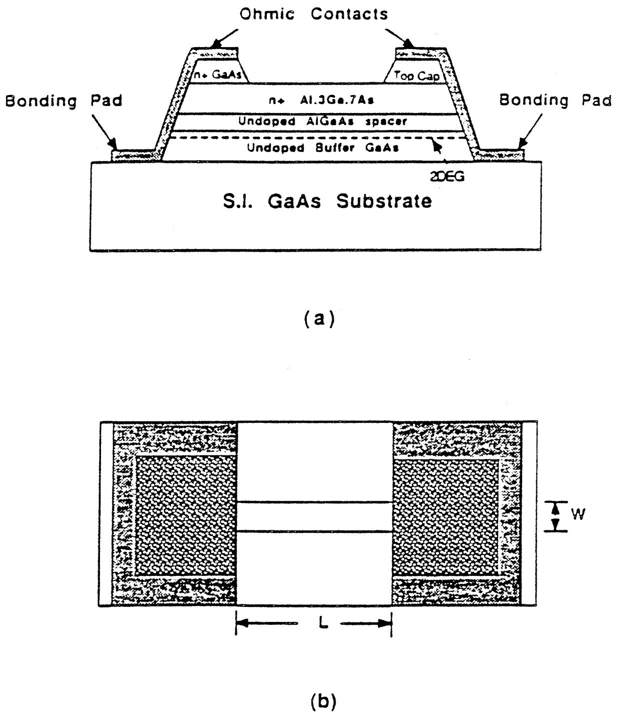
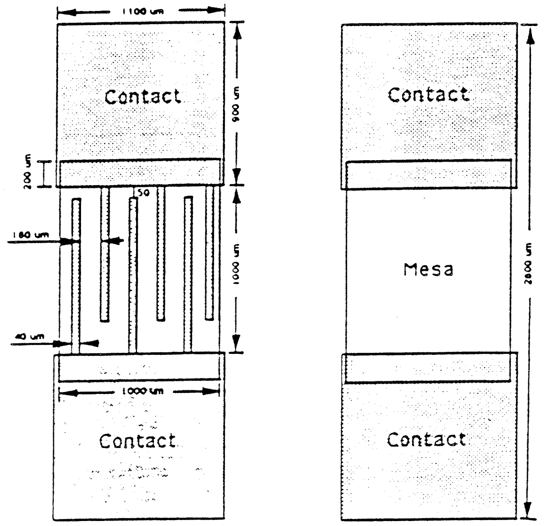


Figure 1: Millimeter wave device configurations: (a) side view; (b) top view.



(a) (b)

Figure 2: THz detector configurations: (a) interdigitated; (b) open faced.

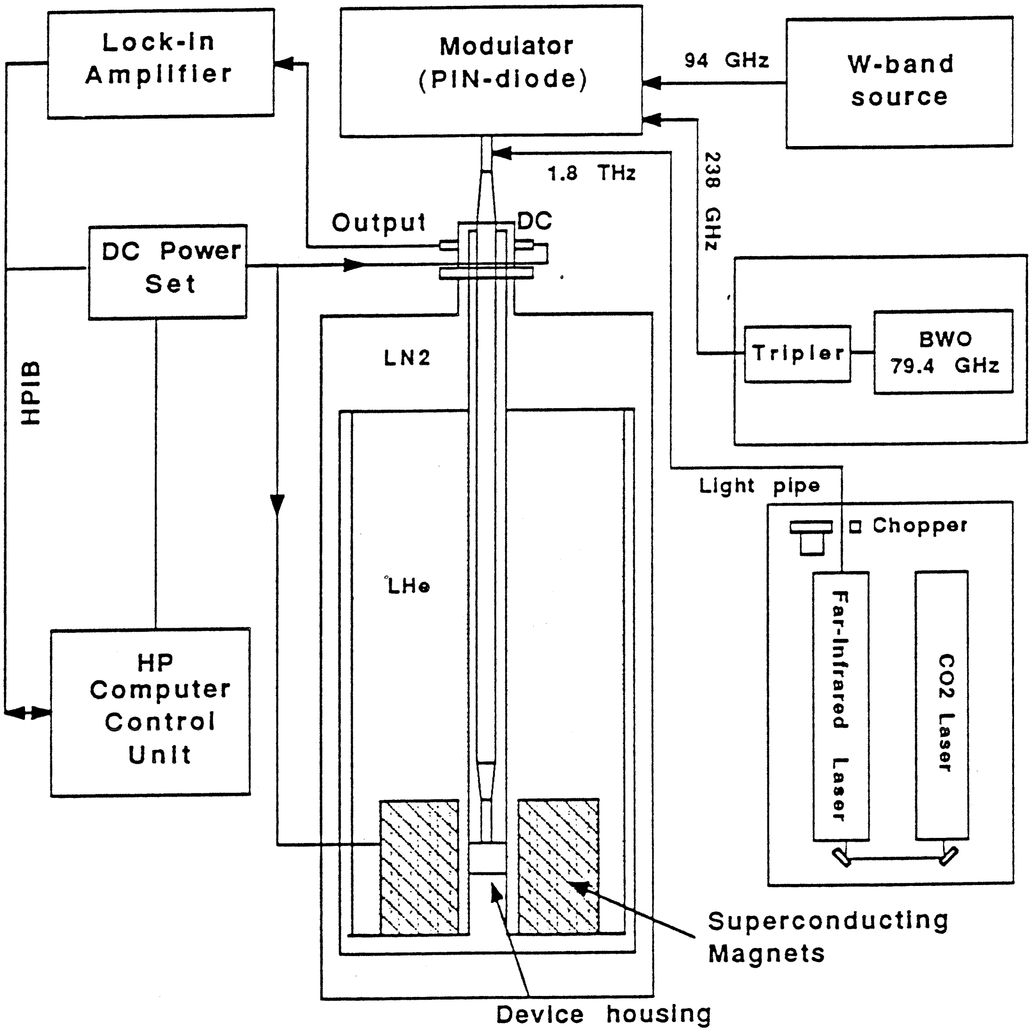


Figure 3: Schematic diagram of the experimental system set up.

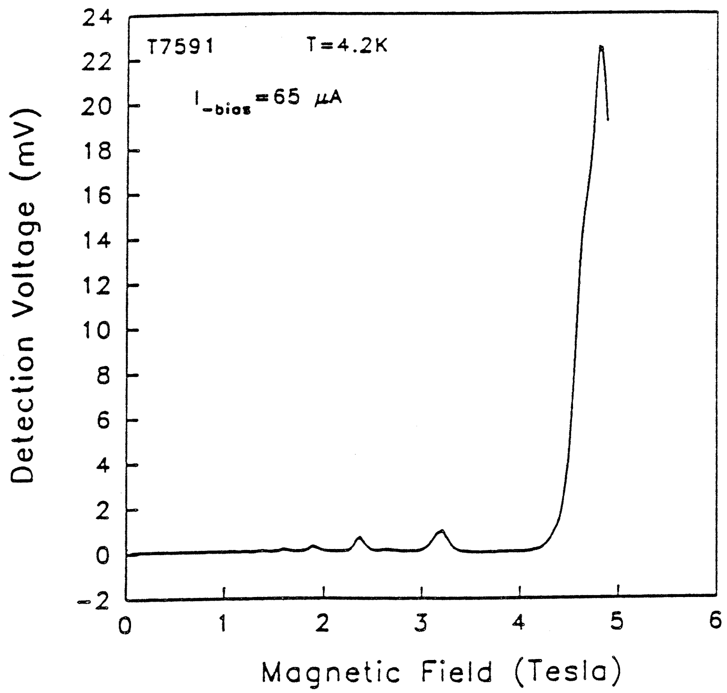


Figure 4: Detector response at 1.8 THz; MBE sample with $\mu_{4K} = 7.9 \times 10^5 \text{cm}^2/\text{Vs}$.

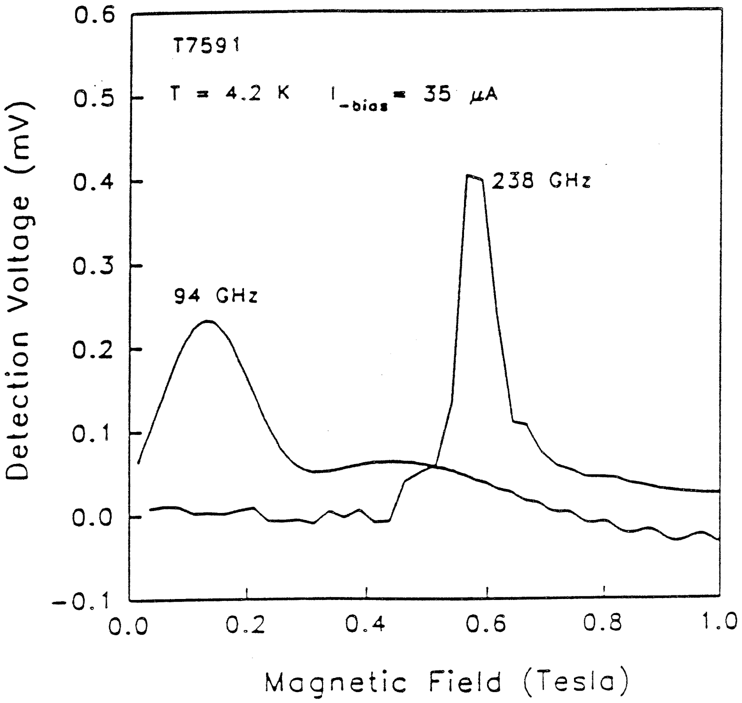


Figure 5: Detector responses at 94 GHz and 238 GHz, same material as in Figure 4.

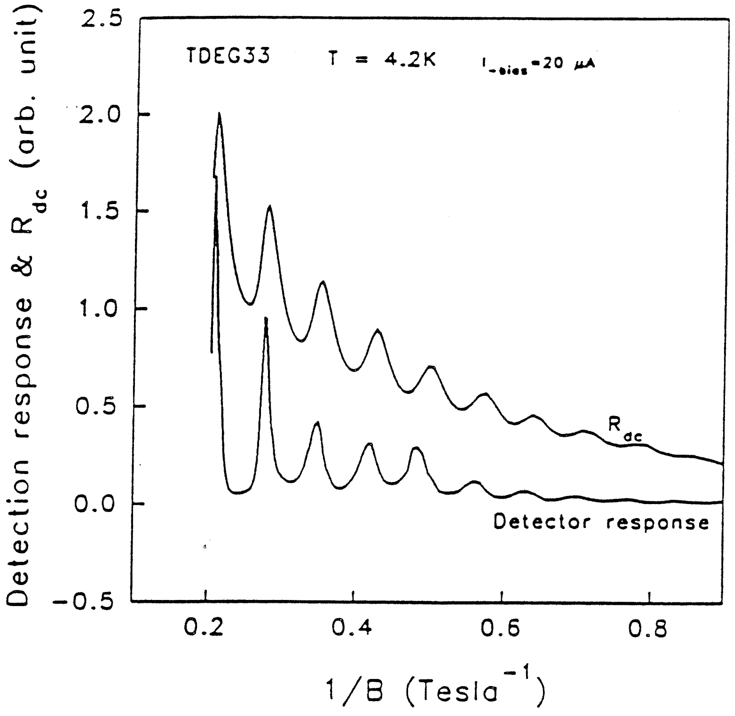


Figure 6: Detector response and device resistance vs. 1/B; OMVPE sample with $\mu_{4K} = 7.4 \times 10^5 \text{cm}^2/\text{Vs}$.

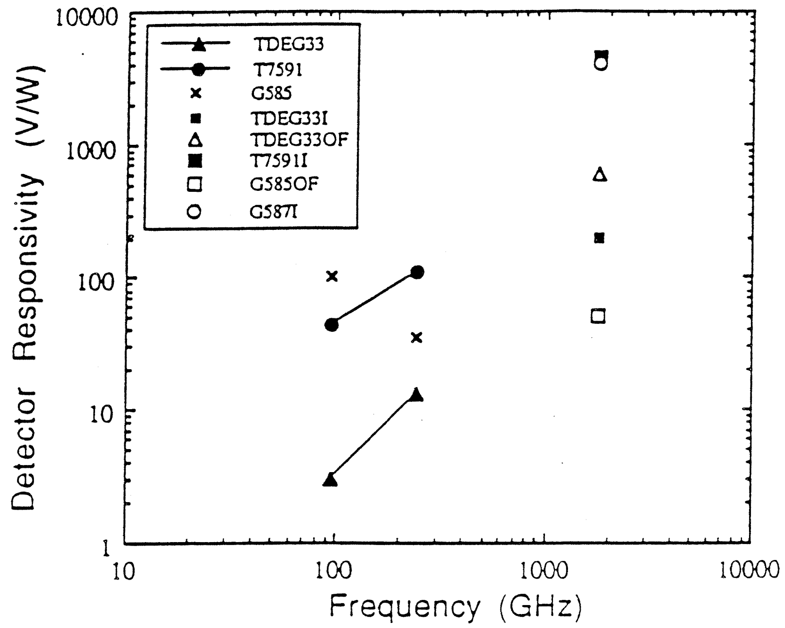


Figure 7: Detector Responsivity vs. Frequency for several different samples.

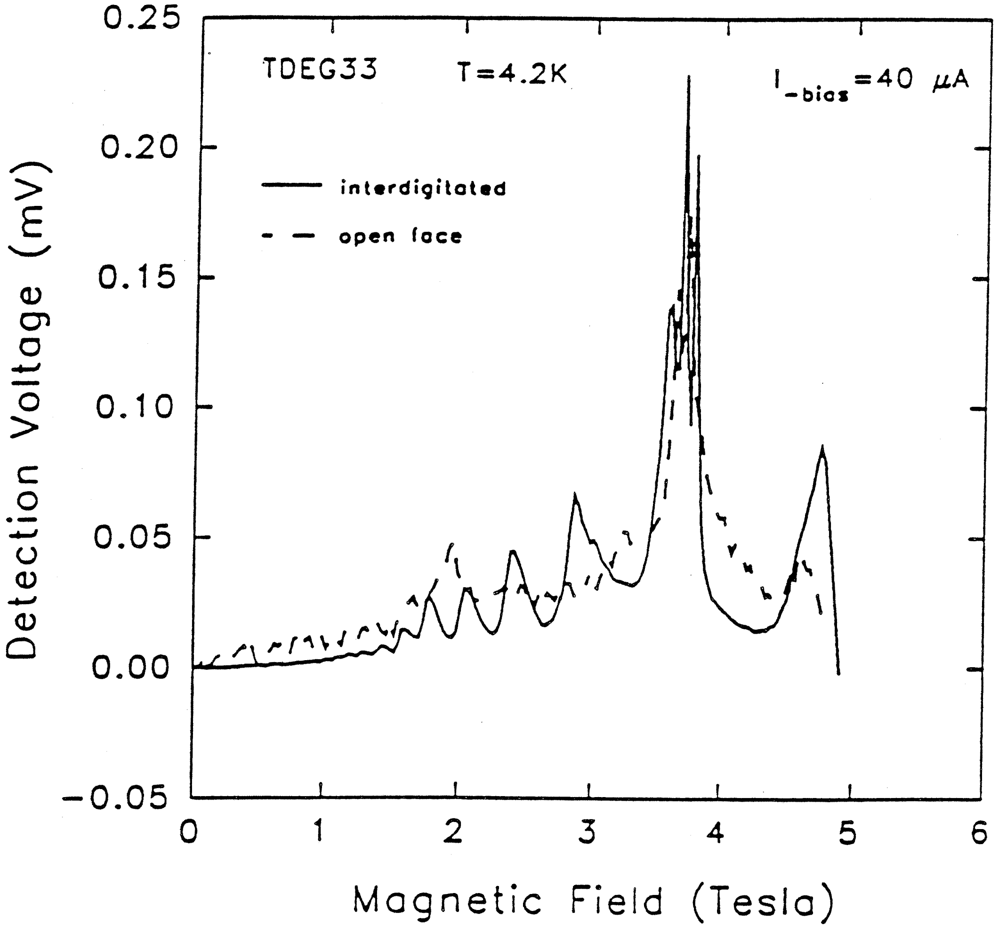


Figure 8: Detector response at 2.4 THz; same OMVPE material as in Figure 6.

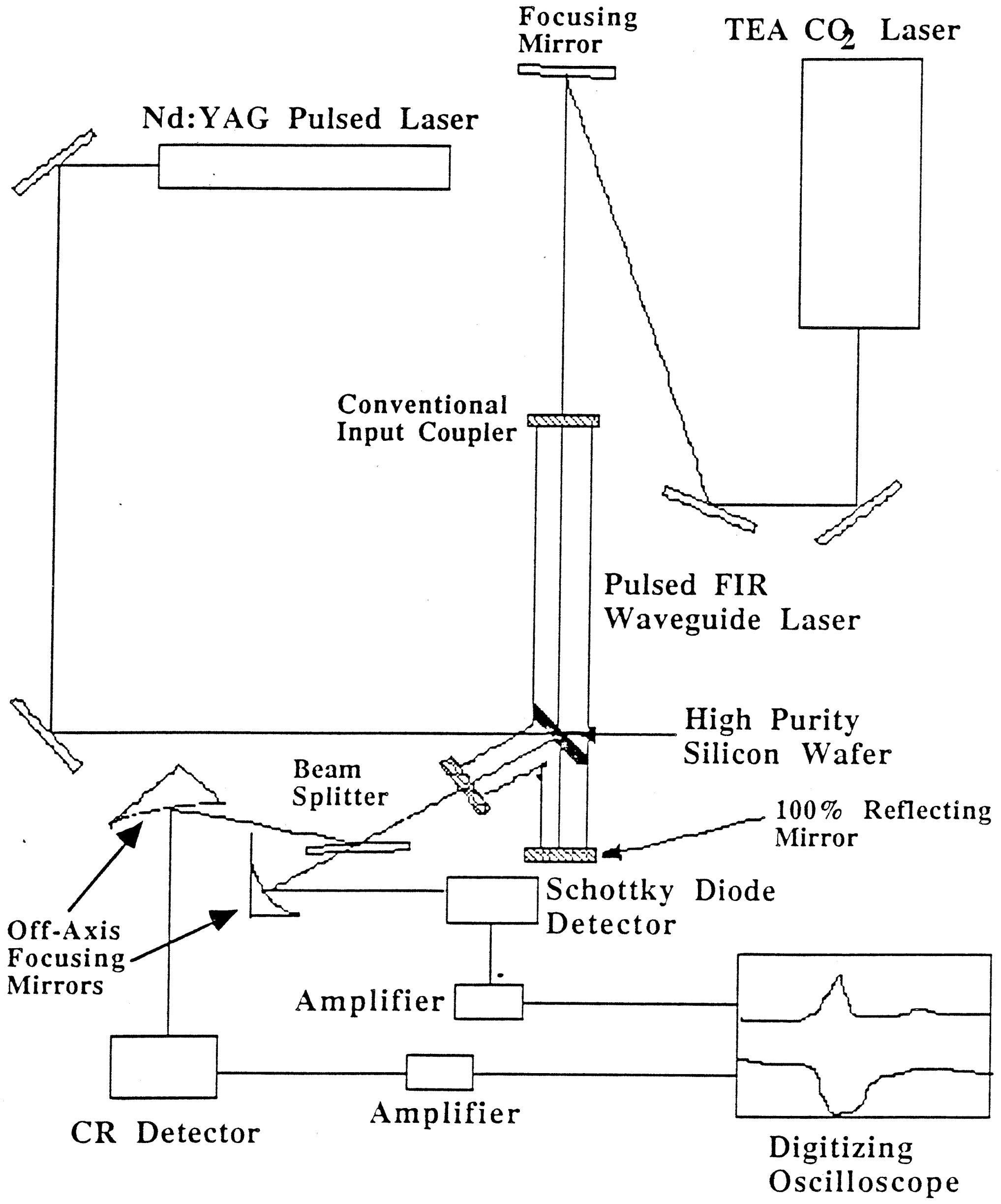
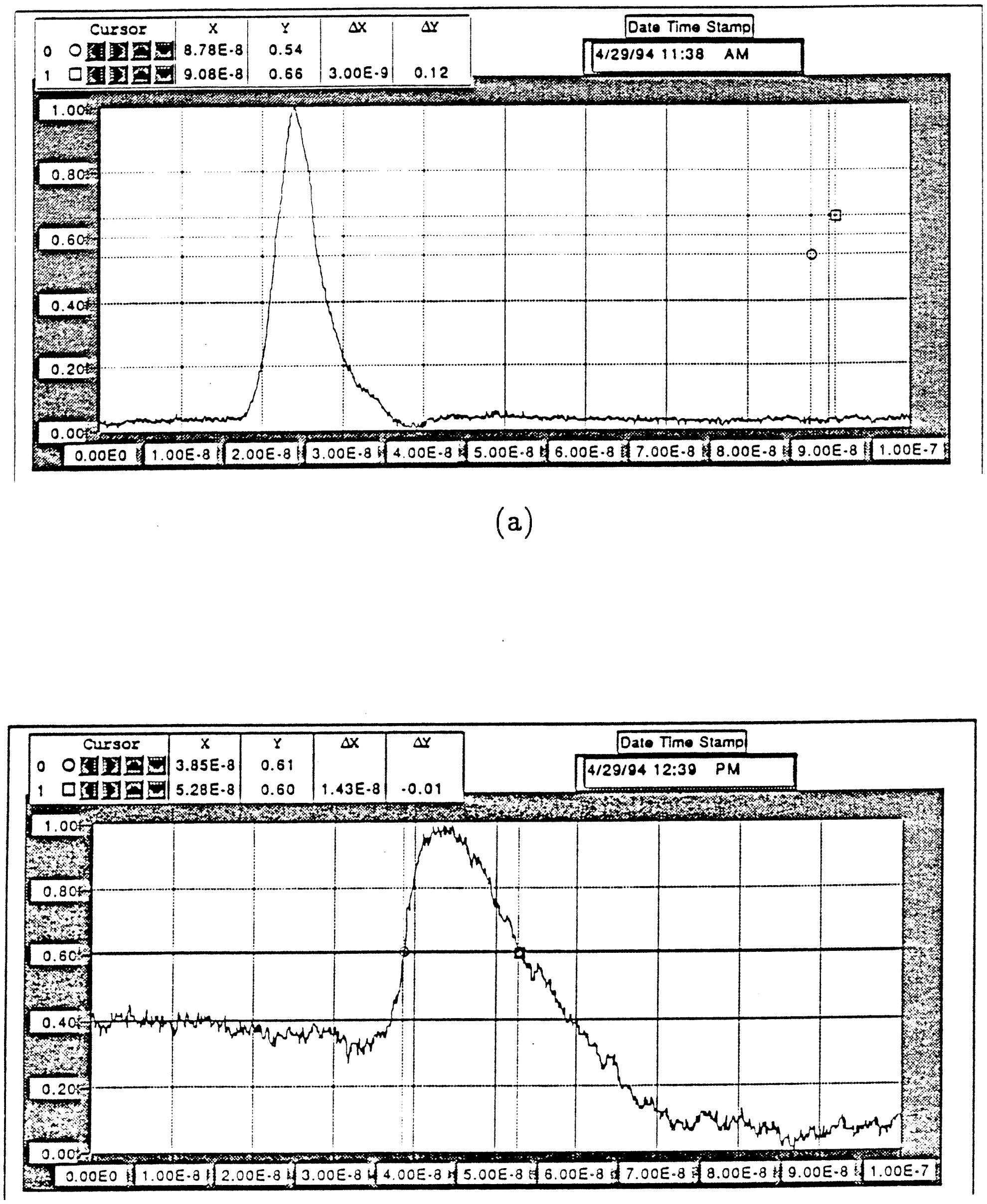


Figure 9: Diagram of the pulsed laser setup.



Cursor	X	Y	ΔX	ΔY
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1 ☐	9.08E-8	0.66	3.00E-9	0.12

Date Time Stamp
4/29/94 11:38 AM

(a)

Cursor	X	Y	ΔX	ΔY
0 ○	3.85E-8	0.61		
1 ☐	5.28E-8	0.60	1.43E-8	-0.01

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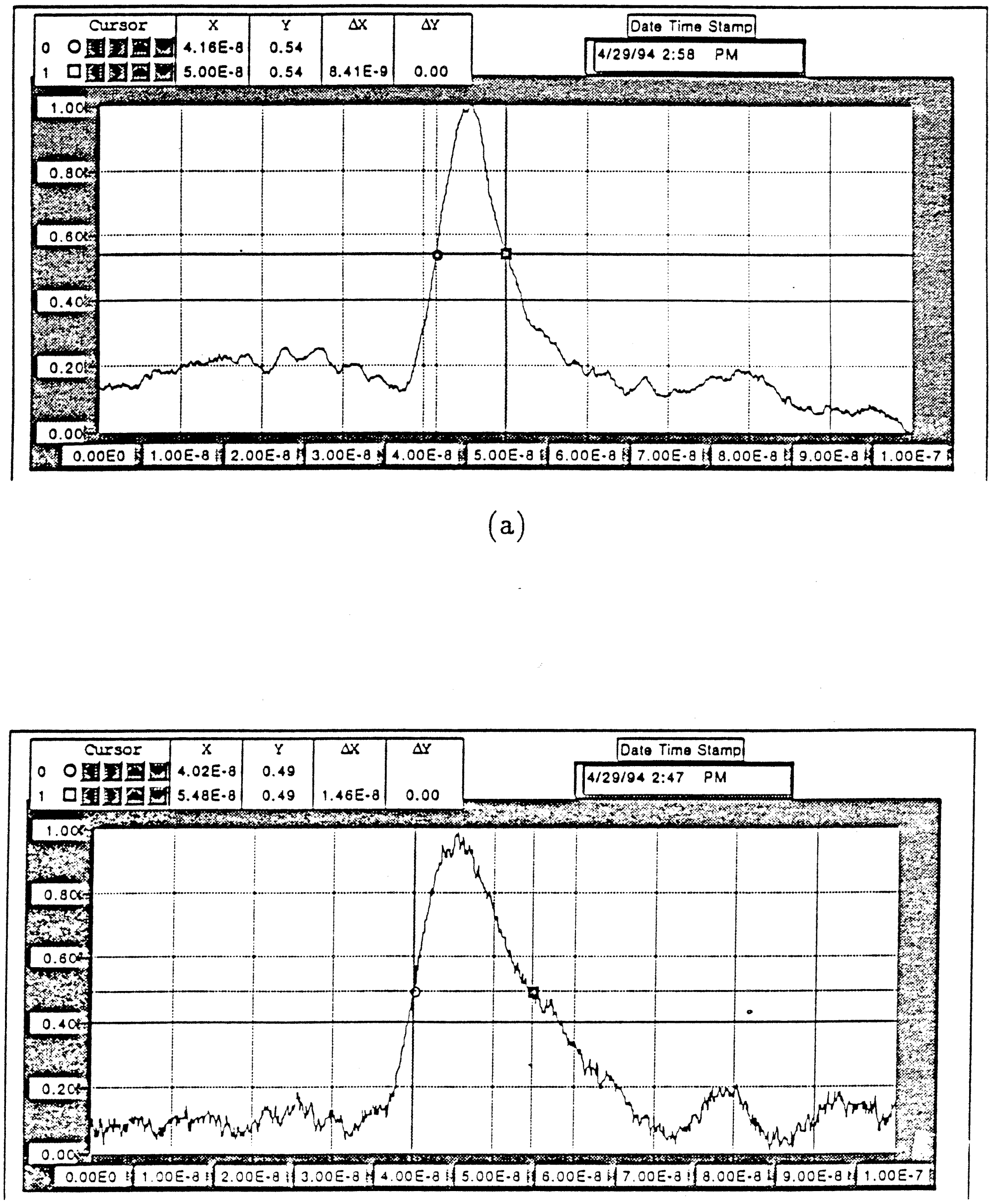
(b)

Figure 10: Pulse detection at 1.2 THz; (a) Schottky detector; (b) CR detector.



Cursor	X	Y	ΔX	ΔY
0 ○	4.16E-8	0.54		
1 □	5.00E-8	0.54	8.41E-9	0.00

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(a)

Cursor	X	Y	ΔX	ΔY
0 ○	4.02E-8	0.49		
1 □	5.48E-8	0.49	1.46E-8	0.00

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(b)

Figure 11: Pulse detection at 0.6 THz, employing the CR detector with a magnetic field of (a) 1.5 Tesla; (b) 2.9 Tesla.

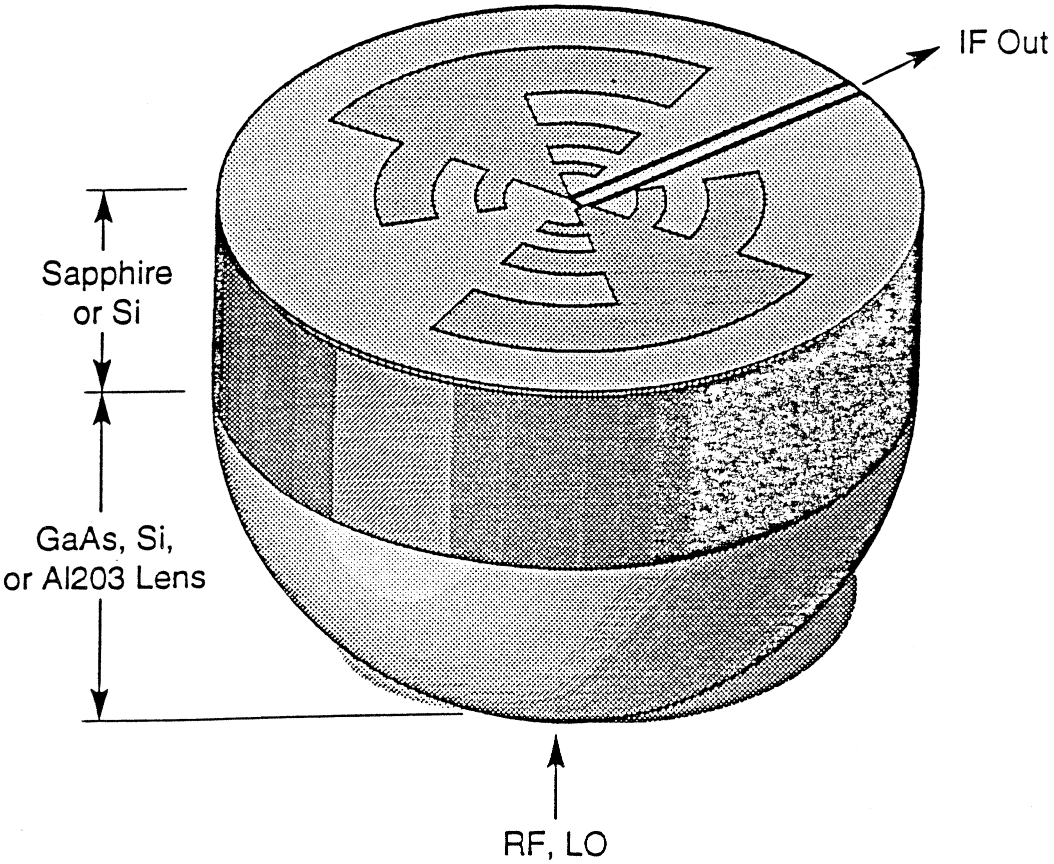

Figure 12: Quasi-optical coupling structure for the THz 2DEG hot electron heterodyne detector.