FINAL REPORT : FOCAL PLANE ARRAYS FOR SUBMILLIMETER WAVES USING TWO-DIMENSIONAL ELECTRON GAS ELEMENTS, A GRANT UNDER THE INNOVATIVE RESEARCH PROGRAM

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ABSTRACT

This final report describes a three-year research effort, supported by the NASA Innovative Research Program, aimed at developing new types of THz low noise receivers, based on bulk effect ("hot electron") nonlinearities in the Two-Dimensional Electron Gas (2DEG) Medium, and the inclusion of such receivers in focal plane arrays. 2DEG hot electron mixers have been demonstrated at 35 and 94 GHz with three orders of magnitude wider bandwidth than previous hot electron mixers, which use bulk InSb. The 2DEG mixers employ a new mode of operation, which was invented during this program. Only moderate cooling is required for this mode, to temperatures in the range 20-77 K. Based on the results of this research, it is now possible to design a hot electron mixer focal plane array for the THz range, which is anticipated to have a DSB receiver noise temperature of 500-1000K.

The original proposal envisaged the development of a hot electron mixer operating at liquid helium temperature, and tuned to cyclotron resonance by a magnetic field. A millimeter wave and THz detector was demonstrated by Smith, Cronin et al. (1987) following this approach. In our work on this grant, we have found similar results to the Cronin group (resident at the University of Bath, UK). Neither group has so far demonstrated heterodyne detection in this mode, however. We discovered and explored some new effects in the magnetic field mode, and these are described in the report. In particular, detection of 94 GHz and 238 GHz, respectively, by a new effect, "Shubnikov de Haas detection", was found to be considerably stronger in our materials than the cyclotron resonance detection.

All experiments utilized devices with an active 2DEG region of size of the order of 10-40 micrometers long, and 20-200 micrometers wide, formed at the heterojunction between AlGaAs and GaAs. All device fabrication was performed in-house. The materials for the devices were also grown in-house, utilizing OMCVD (Organo Metallic Chemical Vapor Deposition). In the course of this grant, we developed new techniques for growing AlGaAs/GaAs with mobilities equalling the highest values published by any laboratory.

We believe that the field of hot electron mixers and detectors will grow substantially in importance in the next few years, partly as a result of the opportunity given us through this

grant, which represents the major effort in the US so far. We note, however, that parallel research on hot electron mixers in thin film superconductors in Russia, and recently in Sweden, have demonstrated mixing up to 1 THz, with the potential for low-noise receivers for frequencies up to many THz. The three groups recently assessed the relative advantages of 2DEG and superconducting film mixers in a joint paper (Kollberg et al., 1992; see Appendix II).

INTRODUCTION

Background- Hot Electron Mixers

Remote sensing from outside the earth's atmosphere, as well as astronomical observations from space-based platforms, ideally should involve the entire electromagnetic spectrum. Recognizing this, NASA has supported development of instruments for what is now termed the "THz Range", which we may define as the frequency span from 0.3 THz to 30 THz (wavelengths 1 millimeter to 10 micrometers). This spectral region is especially important for realizing astronomical objectives, such as studying star formation and the interstellar medium, while being equally essential for remote sensing investigations of the earth's atmosphere, which can improve our fundamental climatological models. Recent reviews of the objectives and requirements of NASA's THz Program are given by Frerking (1991) and Siegel (1991). The effort on this grant addressed the following technology goals for the THz program:

(i) Development of low-noise receivers for 400 GHz to 1.2 THz, with later extension to 3 THz for astronomy missions, and development of remote sensing receivers to 640 GHz. Astronomy receivers are required to reach the lowest noise temperatures possible, and are consequently anticipated to utilize cooling to liquid helium temperatures (4K or below). Remote sensing needs are for receivers with excellent reliability and long-term performance, and are more flexible in terms of noise temperature. These receivers may therefore operate at anywhere from 20 K to 300 K.

(ii) Focal plane arrays, which allow observations to proceed in parallel over an extended area of the sky, constituting a number of pixels of an image, thereby increasing the effective detection speed by a factor which is ideally equal to the number of elements in the array. Such arrays are envisaged for spectrometer receivers, as well as for straight detectors, and could be usefully employed throughout the entire THz range.

Detection speeds of THz receiver systems can best be increased by decreasing the receiver noise temperature. The best results for double-sideband (DSB) receiver noise temperatures versus frequency in 1988, were as shown in Figure 1 (the fulldrawn lines). A conspicuous feature of this diagram is the excellent noise temperatures achieved by InSb "hot electron", bulk-effect, mixers in the frequency range from 0.4 to 0.8 THz. The main disadvantage of the InSb hot electron mixer has always been the narrow bandwidth, about 1 MHz. This makes it particularly impractical for THz use, where spectral coverage of about 1 GHz may be required. Other known hot electron mixers, for example using bulk GaAs, suffer from the same limitation. Demonstrating a hot electron mixer with wide bandwidth was thus a major goal in our work.

A hot electron mixer device is really a bolometer, but one which relies on heating of only the electrons, rather than the entire crystal lattice (the latter represented by the phonons). The electron system can often be characterized by an "electron temperature" (T_e). Due the low specific heat of the electrons compared with the phonons, an electron bolometer can be very sensitive, and it also responds relatively fast. Its response time is determined by the characteristic time for the interaction between the electron and phonon systems, the "energy relaxation time", τ_e. The energy relaxation time for InSb has been found to be from 10^{-7} s to 10^{-6} s. The bandwidth of the mixer is inversely proportional to the response time, or more precisely

$$B = \frac{1}{2\pi\tau_e} \tag{1}$$

Hence the bandwidth limitation for the InSb mixer. As will be shown in detail below, the energy relaxation time of the 2DEG medium has been measured in this work to be about 2×10^{-10} s for electron temperatures below about 20 K, and 1×10^{-10}s at $T_e = 85$ K. The corresponding bandwidths are 0.8 GHz and 1.7 GHz. The bandwidth thus has been increased by three orders of magnitude compared with previous hot electron mixers.

Since the proposal for this IRP was written in 1988, improved noise temperatures for other types of receivers have been obtained, as also indicated in Figure 1 (dotted lines). So far, SIS mixers have become considerably lower in noise up to about 500 GHz, using Nb tri-layer junctions. Above about 700 GHz, one requires a superconducting material with a larger bandgap than Nb, such as NbN, but these mixers have so far not demonstrated very low noise. Note that the receiver noise temperatures in the frequency region above 500 GHz have not changed very much, however. This is the band at which our effort was aimed. Although no noise measurements were taken during the period of this grant, we estimate that it will be possible to reach DSB receiver noise temperatures of 500 to 1000 K in the frequency range 500 GHz to 1 THz.

Background - Focal Plane Arrays

A recent trend in millimeter and submillimeter wave receiver systems has been toward integrating receiver elements with antennas (Rutledge et al., 1983, Yngvesson, 1983, Yngvesson, 1988, Rebeiz, 1992). This is especially advantageous if an entire array of antenna elements is placed in the focal plane of a lens or a reflector antenna, resulting in a system which is capable of imaging. In order to sample the image, and recover all information contained in it, one should ideally place the antenna elements at a spacing given by the Nyquist sampling criterion (Rutledge et al., 1983). It can be shown that no antenna array can be constructed with its elements at this spacing, without losing a considerable fraction of its optimum coupling efficiency (Johansson, 1988). Efficient arrays have element spacings of 2 to 3 times the Nyquist spacing, and are said to undersample the image by the same factor.

Several types of antenna elements have been shown to couple especially efficiently to the radiated field, see (Rebeiz, 1992). For example, an element of the type used in an array of tapered slot antennas (TSAs) was shown to have a coupling efficiency within 0.5 dB of that of a pyramidal waveguide horn, by a direct substitution measurement (Kim & Yngvesson, 1990). This measurement was done at 35 GHz. Another type of efficient array element is the integrated horn array of (Rebeiz et al., 1987), which consists of pyramidal horns, etched in silicon substrates, integrated with pick-up antennas on a silicon-oxy-nitride membrane. Both types of arrays can be used at undersampling factors of about 2 to 3, whereas arrays of corrugated horns have better coupling efficiency, but undersample by about a factor of 4.8 (Erickson et al., 1987). Because of the demonstrated performance of the TSA arrays at frequencies up to 94 GHz, we proposed to develop versions of these which could be integrated with the 2DEG mixer devices, and fabricated at THz frequencies. It was clear that a good approach might involve direct fabrication of the antennas from silicon or GaAs substrates.

Design Criteria for a Practical Hot Electron Mixer

By examining the features of existing receivers critically, one can define the following criteria for a new approach to THz receiver design:

(i) It is desirable to use the bulk effect, due to the low parasitics which are guaranteed with this approach.

(ii) Monolithic integration of the device on an integrated transmission line (microstrip, slot line, etc.) is more advantageous than the waveguide coupling employed in InSb mixers.

(iii) The monolithic integration technology ought to be combined with integration with a focal plane antenna array element.

(iv) The approach chosen might take advantage of recent advances in semiconductor growth and device fabrication technology, including what is often termed "bandstructure engineering".

(v) Most importantly, the bandwidth must of course be drastically increased, without compromising the conversion loss and the noise temperature. It was clear that this was possible, at least in principle, since several semiconductor materials were known to exhibit much shorter energy relaxation times than the InSb device, see for example Conwell (1967), (Sakaki et al., 1984), and Shah (1986).

Some of the above criteria had been pointed out by (Smith et al., 1987). This paper described a detector employing cyclotron resonance of the two-dimensional electron gas (2DEG), trapped at a hetero-junction formed from AlGaAs and GaAs. We decided to use the same basic medium, but also to especially emphasize points (ii), and (iii), based on our own experience in these areas, while Smith et al. (1987) employed a waveguide configuration similar to what had been the typical practise for InSb mixers. We were also eager to explore the many possible "variations on a theme" available to us by growing different hetero-structures, for which we had extensive experience based on an in-house OMCVD (Organo-Metallic Chemical Vapor Deposition) system.

Our plan had another element which we believe was important: the application of a recently developed technology, hetero-structure engineering, to a new area, THz space technology. A vast base of information was available about hetero-structures from other device and basic research (very high speed transistors, etc., also note the Quantum Hall Effect area).

Overview of Work on the Grant

Most of the first year of this effort was spent ordering and setting up major pieces of equipment, such as the liquid helium dewar and the superconducting magnet. We also developed our initial techniques for growth of the hetero-structure material, and fabrication of the devices. During the second year, we started to test our first devices as detectors at 94 GHz, using the mode of operation proposed by Smith et al.(1987), i.e. with the device tuned to cyclotron resonance. We were able to duplicate the results of Smith et al. at this frequency, with a somewhat lower responsivity. No heterodyne detection was found, however. Instead, we invented a new mode of operation for the device, in which the electrons are heated to a considerably higher value of T_e, from 80 to 100 K. In this mode, we demonstrated efficient mixing. In order to organize our report we will distinguish three different modes of operation of our 2DEG devices:

Mode I:

In this mode, the device is heated by a DC bias current of several mA's, and LO power of about 1 mW, whereupon T_e reaches values of 80-100 K. No magnetic field is utilized, and the lattice temperature is typically 20 K, although in some experiments it was 4.2 K, and in others 77 K. Efficient mixing has been obtained.

Mode II:

In Mode II, the device is cooled to the liquid helium temperature range, and a magnetic field is applied. The bias current is much smaller (about 10 microamp), and T_e is roughly 10 K. No mixing has been demonstrated so far in this mode. There are two different versions of Mode II:

Mode IIa: The Cyclotron Resonance Detector

This is the mode originally proposed by Smith et al.(1987), i.e. the 2DEG is tuned to cyclotron resonance. The magnetic field is about 0.2 T for a frequency of 94 GHz.

Mode IIb: The Shubnikov-DeHaas Detector

This mode occurs at a higher magnetic field than Mode IIa, in the range 1-4 T.

Outline of the Report

All experiments utilized the same basic device structure, the main difference being that the device length and width were changed. The basic device structure and fabrication is therefore described first in what follows. After this follow our results for the different Modes of operation, summary of results for the growth of the materials, and results on focal plane arrays. Finally, we give our conclusions, and suggestions for further work.

2DEG DEVICE CONFIGURATION AND TEST SETUP

We developed a two-terminal device structure, as shown in Figure 2. The sequence of layers grown is the same as is used for AlGaAs/GaAs Hetero-junction Field Effect Transistors (HFETs). The device is contained within a mesa, which is surrounded by semi-insulating GaAs for isolation. A standard sequence of metals is deposited in an E-beam evaporator for forming Au/Ge ohmic contacts. The device pattern is then defined by a lift-off process. Gold plating may also be used to build the metalization up to sufficient thickness. A thin ("cap") layer of heavily doped GaAs facilitates the formation of good ohmic contacts. This layer is etched off in the active area of the devices, after these have been defined. The device thus consists of large contact pads, with a small gap (length L, width W), through which the current flows in the 2DEG. The latter is formed on the GaAs side of the AlGaAs/GaAs hetero-junction. Wafers are finally thinned to 125 micrometers, and cut into small chips by scribing. The chips are soldered to a microwave circuit, etched in the metalization of a substrate (either Duroid or silicon). Figure 3 illustrates a typical microwave circuit used in a 94 GHz mixer, and the "flip-chip" technique for soldering the chip to the circuit. Further details regarding device fabrication, etc., can be found in (Yang, 1992).

The impedance of the device will be essentially resistive, with a value of

$$R_B = \frac{L}{W} * \frac{1}{en_s\mu} \tag{2}$$

Here, n_s is the density of carriers per cm^2, and μ the mobility in cm^2/Vs. A great advantage of the two-dimensional medium is the fact that the device impedance can be adjusted easily to match the characteristic impedance of typical microwave integrated circuits (50-100 ohms), by choosing L/W. The value of the second factor in (2) is typically less than 100 ohms, thanks to the fact that both density and mobility can be kept large at the same time. This is possible by the unique configuration of the hetero-junction which defines the 2DEG channel: the doping is situated in the AlGaAs, separated by an undoped spacer layer of about 100 A thickness. Ionized impurity scattering is thus essentially eliminated, allowing the mobility to stay high at low temperatures. Efficient transfer of the electrons to the 2DEG channel, and a high energy barrier which confines them there, result in a high electron concentration, n_s. This is very different from the homogeneous bulk case, such as the InSb mixer device, in which the doping must be kept extremely low in order to maintain a high mobility. The total number of electrons in the device can thus be made much smaller than in the traditional InSb devices - therefore the power level which is required to drive the device nonlinear is much lower, for a given energy loss rate per electron. In other words, the local oscillator power requirements are quite modest. The discussion in this paragraph relates basic properties of the 2DEG medium which had been described in the proposal - what remained to invent was the actual mechanism to make the device nonlinear, which we shall describe in the sections on results.

The microwave circuit substrate is inserted into a split metal block, so that the narrowing slot becomes a finline circuit, which can be connected to a standard waveguide. We chose this method for the initial testing of the mixers, due to its compatibility with the geometry of a tapered slot antenna. It also allowed us to perform accurate measurements of the conversion loss of the mixers. We intend to eventually integrate the device with a TSA as shown in Figure 4. If the TSA is fabricated from the GaAs substrate, on which the device structure has been grown and defined by photo-lithography, then the final result will be a monolithically integrated antenna/mixer with a minimum of parasitic reactance, ideal for THz frequencies.

In our measurements so far, we have cooled the mixer by employing one of the following (i) immersion in liquid helium in a dewar, with built-in superconducting magnet (maximum field 5 T), (ii) a closed cycle refrigerator, capable of producing temperatures down to 15 K, or (iii) conductive cooling from liquid nitrogen, contained in a simple dewar.

RESULTS

The results of our investigation will be described quite briefly below, in order to illustrate the variety of useful information obtained and applications realized. More extensive papers have been or will be written on the different sub-topics, as referred to in the text which follows.

Two-Dimensional Electron Gas Mixers

Mode I 2DEG Hot Electron Mixer

As mentioned earlier, a new mode of operation of a hot electron mixer, employing the 2DEG device, was discovered. An invention disclosure was submitted in 1989, describing the new device and its operation (Yngvesson, Lau and Yang, 1989).

The Mode I mixer exploits the well-known fact that the electron scattering rate in most III-V semiconductors becomes dominated by longitudinal optical phonon processes above a temperature of about 50K. As these processes set in, one finds that the mobility of the electrons decreases strongly as the temperature is increased. It had been shown in work such as that of Shah(1986) that the mobility would follow about the same functional dependence when either the electron temperature or the lattice temperature was varied. In the first case, similar to what occurs in the InSb mixer, the electrons may be heated to T_e, while the lattice stays at a constant temperature T_L. As a result, the mobility will decrease rather rapidly, and the resistance of the device will increase. Measured I-V-curves for three of our devices are shown in Figure 5. (We also tested devices made on a wafer grown by MBE, obtained from the Raytheon Company, Courtesy of Dr. Daniel Masse'. The results for this and our own OMCVD wafers were comparable). If the initial mobility (for low electric field) is very high, this curve will display a substantial nonlinearity, and allow efficient electron bolometric mixing. We have demonstrated such mixers at frequencies of 35 and 94 GHz, so far, with a lowest conversion loss of 18 dB (Yang et al, 1993). The conversion loss can be predicted from the I-V-curve, by extending the theory of (Arams et al., 1967). We find very good agreement between theory and experiment, as shown in Figure 6. We have also projected the performance of future mixers, using I-V-curves which should be realizable by improving our fabrication of the devices. These calculations predict that conversion loss of about 10 dB is feasible. At the operating point, $T_e = 85$ K, and the lattice temperature may be from 20K to 77K. It is interesting to note that the performance of our 2DEG mixer depends quite directly on the extremely high mobility at low temperatures for which the 2DEG in AlGaAs/GaAs is famous. Another device, the HFET, which was originally named the HEMT, or High Electron Mobility Transistor, uses the same 2DEG medium, but it has been shown that the high mobility (at low electric fields) is not essential to its operation.

As anticipated, we measured a very wide bandwidth (1.7 GHz) for the 2DEG mixer, about three orders-of-magnitude wider than for the InSb device, see Figure 7. From (1), we find a value for τ_e of 10^{-10} s. The bandwidth can potentially be increased further since energy relaxation times as short as 10^{-11} s have been measured in this temperature range (see Shah, 1986). Future THz receivers require a somewhat wider bandwidth, and this could thus be a new development goal.

We have so far not measured the noise temperature of any of the mixers. A calculated estimate predicts a value of the DSB receiver noise temperature of 500-1000K, which should be attainable at about 1 THz.

The successful operation and theoretical modeling of the Mode I mixer was a major result in the Ph.D. thesis of J.-X. Yang (Yang, 1992). The 35 GHz measurements were part of the M.Sc. thesis of Wes Grammer (Grammer, 1992).

Use of the cyclotron resonance in the 2DEG for detection of THz radiation (Mode IIa).

With the addition of a quantizing magnetic field which is perpendicular to the 2DEG plane, electrons may also be heated up by the absorption of microwave power. The mechanism of this type of hot electron effect is quite different from the one that we have discussed in the previous sections, because the energy of the electrons is now quantized into Landau levels. The Landau quantization can be expressed as

$$E_{np} = E_n + \left(p + \frac{1}{2}\right) \hbar\omega_c \tag{3}$$

$$n = 0, 1, ...; p = 0, 1, ...$$

where E_n is the bottom of the n-th subband energies of the 2DEG and ω_c the cyclotron resonance (CR) frequency, given by $\frac{eB}{m^*}$ (where e is the electron charge, m^* the electron effective mass, and B the flux density of the magnetic field).

When the signal frequency ω is equal to the cyclotron frequency ω_c, electrons will absorb the signal power resonantly. Such a resonant absorption process may result in a change in the electrical resistivity (or conductivity), either an increase or a decrease. One may therefore utilize this type of heating effect for the signal detection, as shown by Smith et al. (1987). In general, the CR-type detection is subject to two fundamental conditions: (1) $\omega_c \tau_m > 1$ and (2) $\hbar\omega_c > k_B T$, where τ_m is the electron momentum relaxation time. At low temperatures these conditions imply that the CR effect can be better resolved at high frequencies and thus this mode will be suitable for high frequency applications. We measured the CR response of a 2DEG device in a setup similar to the one described above, at 94 GHz and 238 GHz, respectively (see Figure 8).

It is seen that the CR photoresponses are well resolved at these two nearby frequencies, and that the responsivity is essentially independent of frequency. In our preliminary experiments, the measured detector responsivity is much lower than that obtained by Smith et al., (1987). We believe that this difference is mainly due to the materials used. To enhance the CR heating effect, the mobility of the device should be high, and the sheet electron density (n_s) should be low (Yang, 1992). Further experiments on samples with ultra-high mobilities ($> 10^6$ cm^2/V-s) and low n_s (in the low 10^{11} cm^{-2}) are currently being performed at the University of Massachusetts, on a new NSF grant.

The position of the Fermi energy (E_f) relative to the adjacent Landau levels is an important factor which affects the detector responsivity. However, the sheet charge density n_s, which is proportional to E_f, is not easy to accurately determine in the material-growth cycle. An alternative way to accomplish this by introducing a third Schottky-type contact (gate) near the center of the 2DEG channel was proposed in (Yang, 1992). This gate should be short and thin ("semi-transparent") to avoid causing loss to the incident signal. Changing the voltage between the gate and the source will change the depletion depth in the heavily doped *AlGaAs* layer, and will, in turn, change the number of electrons tunneling to the 2DEG channel from the AlGaAs layer. Unlike the usual operational configuration for traditional three terminal devices such as HEMTs, the gate here is only for providing a DC voltage to the channel and is not involved in any part of the high frequency circuit.

The CR-type mixer was also attempted experimentally in this research. The idea was originally motivated from the successes of the bulk *InSb* CR mixers (Brown, 1985) and the strong CR detection in the *AlGaAs/GaAs* heterostructures measured by Smith et al., (1987). When the bias current in our experiments was as small as a few tens of μA, no CR mixing was observed. The responsivity of the corresponding CR detection for these devices was only about 0.5 V/W. Assuming the Mode I hot electron mixer theory to be still valid, a high conversion loss ($\simeq$ 85dB) is then expected in this case. In order to decrease the mixer conversion loss and still maintain the feature of low bias current, the responsivity must be increased to of the order of 2500 V/W, for which L_c = 20 dB is predicted at I_{bias} = 50 μA. Note that Smith et al. (1987) actually measured a responsivity of about 250 V/W which is only an order of magnitude lower than this criterion.

As the current was increased to a few mA, however, a clear and sharp *peak* in mixer conversion loss was observed at a magnetic field exactly matched to the CR condition. Figure 9 shows the experimental result for a 94 GHz mixer. The result was just the opposite to that desired, i.e., the conversion loss suddenly becomes very high at the cyclotron resonance magnetic field. Based on the experimental results shown in the previous section, the electron temperature in this case was about 100 K due to the DC heating. According to the theory for cyclotron resonance, no CR-related phenomenon should be observable because of the high thermal energy ($k_B T_e$ = 8.6 meV) compared with the Landau level spacing (0.39 meV). The result shown in Figure 9 is thus unexpected and represents a very interesting lead for future research.

<u>An alternative to the cyclotron resonance detector: The Shubnikov DeHaas device (Mode IIb)</u>

When the magnetic field is sufficiently high so that $\omega << \omega_c$, a strong oscillating signal was observed in the detector experiments. The phenomenon is similar to the DC Shubnikov de Haas (*SdH*) oscillation. The DC *SdH* effect is evidenced by a periodic variation of the resistance (R_{xx}) of a semiconductor sample, as the magnetic field (B) is varied. The period of oscillation can be determined by plotting R versus $1/B$ (see e.g. Sakaki et al., 1984). The SdH effect is a quantum-mechanical effect, which can be explained by the crossing of the Landau levels (see (3)) with the Fermi level. Unlike the CR-type detector, the SdH-type detector can always detect a signal at any magnetic field as long as the condition $\omega << \omega_c$ still holds. To explore the potential applications of this quantum effect, we have experimentally investigated the SdH-type detection utilizing the $AlGaAs/GaAs$ 2DEG devices as detectors at millimeter wave (MMW) and near submillimeter wave (SMMW) frequencies. We expect that this new type of detector may possibly be used for low-noise detection in the THz frequency region.

Figure 10 shows typical measurement results of SdH detection at 94 GHz and 238 GHz, respectively, with approximately the same illumination powers. The device and the circuit used were the same as were used in the CR-type detector experiments. Strong oscillating responses occurred, preferentially at high magnetic fields. The oscillations show exactly the same period at these two frequencies, if plotted versus $1/B$, and their magnitudes are also basically the same. This indicates that the SdH detection is independent of (or at least insensitive to) the input signal frequency, indicating a nonresonant absorption process. As in the DC SdH effect, the well-developed periodicity of the detected voltage which results from the electron heating must have a direct relationship with the detailed energy structure of the electron gas, i.e., the Landau levels. The relationship to the DC SdH effect has been confirmed by comparing the measured R_{xx} for the detector device with the measured R_{xx} for a standard Hall bar in which the contact effects were minimized. We found an exact match of the oscillation periods between these two separate experiments, and therefore concluded that the detected oscillating signal is due to the SdH effect. Yang (1992) discusses the interpretation of this new effect in considerable detail.

We have measured the responsivity of the SdH-type detector from W-band to 238 GHz (Figure 11). Within experimental error, the measured responsivity is basically constant over the entire region of the test frequencies, and is about 5V/W on the average. We believe that the frequency-independent responsivity, a feature of free electron detectors, will prevail at even higher frequencies. The device in the experiments was severely mismatched to the microwave circuit due to its very high background magnetoresistance ($\sim$ 2 kohm). One possible solution to improving the impedance matching is to fabricate a set of 2DEG strips in parallel, so that the total resistance of the array can be matched to the microwave circuit. With the improvement in impedance matching, we may then estimate that the responsivity for this type of detector may be increased to at least 50-100 V/W.

Monolithic circuit techniques

In the introduction, we mentioned the desirability of employing monolithic circuit techniques for new THz range devices. We have developed several such new circuits, initially for frequencies up to 40 GHz, for which accurate measurement techniques are available, such as automatic network analyzers and micro-probing. During this phase we employ silicon substrates, which are less expensive and easier to work with than $GaAs$. The dielectric constant of both substrates is very similar, however, and the results can be applied to monolithic circuits on GaAs. The circuit dimensions will be scaled down in order to realize a THz range circuit. Similar techniques are in use for Schottky and SIS mixers, but a major advantage of the 2DEG mixer is that it can be fabricated directly on a semi-insulating $GaAs$ substrate, and that no complicated processes, such as the fabrication of air bridges, etc., are necessary in order to decrease the device capacitance. Several circuits are described in detail in the M.Sc. thesis of Wes Grammer (Grammer, 1992), and in a forthcoming paper (Grammer et al., 1993). As an example of a circuit, we show in Figure 12 a balun from coplanar waveguide to slot-line, and its very wide bandwidth response. Such baluns are used to make a transition from coplanar waveguide (CPW), to the slot-line medium, compatible with the tapered slot antennas which we plan to employ as antenna elements in focal plane arrays. One of several possible mixer designs based on the transition is displayed in Figure 13. The circuits have also been used to characterize the 2DEG device, as discussed below. These circuits often have their correspondence in lower-frequency versions, employing other transmission line media, but the realization in monolithic form has required some innovative techniques for design and testing.

Equivalent circuit of the 2DEG device

The 2DEG device responds to electromagnetic radiation as a bulk device by absorbing the radiation and changing its resistance in response to the power absorbed. The equivalent circuit of the device is therefore ideally a power-dependent resistor, with a value which is independent of frequency. The process by which power is absorbed is free-carrier absorption, and the theory of this process predicts that for extremely high frequencies (close to 1 THz), the carrier response is altered, introducing a phase lag of the current with respect to the applied RF electric field. Such "carrier inertia" phenomena are bound to require study for all future THz devices (see for example (Kollberg et al., 1991)), while the theory for lower frequency devices has been able to ignore these effects. The equivalent circuit of the 2DEG device is predicted to contain an additional inductance in series with the resistance, as shown in Figure 14 (Grondin et al., 1984). In measurements with a microprobe, and utilizing one of the balun circuits described in the previous section, graduate student Wes Grammer was able to confirm the presence of this inductance in the equivalent circuit of the 2DEG device (Grammer, 1992). He had to develop special techniques to perform this microprobe measurement on a device cooled to 77 K. We believe that this is the first measurement of carrier inertia in a modern integrated circuit environment, and also the first for the 2DEG medium. Further experiments of this kind will help us design the THz circuits for the 2DEG mixer, and should also benefit the understanding of other THz semiconductor devices.

Summary of 2DEG growth by OMCVD

During the initial stages of the project, our goal was to utilize fully the nonlinear characteristics of the 2DEG elements for the Model IIa hot electron mixer operation. However, we did not know whether the low temperature mobility (μ) or the sheet carrier density (n_s) should be maximized for the best mixer performance. For HFETs, it was found that high n_s is more important than maximum mobilities. For other device applications of the 2DEG, increase of both the sheet carrier density and mobility lead to an increase of the current handling capability and thus the output power, or improvement of the switching times. Attempts to increase both n_s and μ have been focused on introduction of new hetero-structure designs and material systems. They include strained and pseudomorphic $GaAs/GaInAs$, $AlInAs/GaInAs$, and $InP/GaInAs$ systems and various doping schemes and buffering materials. Here, we focused our attention on improving the conventional *AlGaAs/GaAs* systems by optimizing the epitaxial growth process to reduce undesirable impurity incorporation in individual layers, and to obtain defect-free and smooth hetero-interfaces.

It is well known that the mobility of 2DEG decreases drastically when n_s increases to $> 1 \times 10^{12}/cm^2$, because of intersubband scattering and lower doping efficiency of highly Si-doped ($> 1.8\times10^{18}/cm^3$) *AlGaAs*. Increase of the conduction band discontinuity (ΔE_c) by increasing the *Al* composition in the *AlGaAs* layers would result in a higher barrier for the real space transfer of electrons for a specific doping concentration in the doped layer, and also produce a larger intersubband separation to minimize ionized impurity and intersubband scatterings. The maximum ΔE_c in the *AlGaAs/GaAs* system occurs with 45% *Al* in the *AlGaAs*. However, the growth of high *Al* composition (>25%) *AlGaAs* is always associated with increased DX centers in MBE grown layers, as well as carbon and oxygen incorporation in OMVPE grown layers.

During the early phases of this work, we succeeded in the growth of high quality *AlGaAs/GaAs* 2DEG structures with combined high sheet charge densities and mobilities by low pressure organometallic chemical vapor deposition (LP-OMVPE). We believe the high $n_s\mu$ product was a result of the optimized *GaAs* buffer and *AlGaAs* with high *Al* composition (38%). Undoped *GaAs* layers grown with sufficient thickness for Hall measurements have net carrier concentrations $< 3 \times 10^{14}/cm^3$ and 77K mobility as high as 146,000 cm^2/V-s. The quality of the thin *AlGaAs* layers in the device structures, which were characterized by photoluminescence, was found to be essential to obtain the high $n_s\mu$ product. The sheet charge densities and mobilities at 77K are $1.0 \times 10^{12}/cm^2$ and 95,000 cm^2/V-s for high n_s samples. We believe the combined high values of mobility and sheet carrier density were a result of large conduction band discontinuity (ΔE_c) and low level of deep impurities in the *AlGaAs*. The high ΔE_c was obtained by using a relatively high *Al* composition (38%) in the *AlGaAs* layers, as opposed to the usual 20–30%. With the increased ΔE_c, higher values of n_s can be obtained with a lower donor concentration (n_d) in the doped *AlGaAs* layer. We were able to reduce n_d to 5-7 $\times 10^{17}/cm^3$ while maintaining n_s above $10^{12}/cm^2$. The lower n_d resulted in a reduction of ionized impurity scattering and deep impurity levels associated with *Si* doping in *AlGaAs* systems. Furthermore, there was no noticeable change in the Hall measurements as the surface doped layers were being step-etched, indicating that there was minimal conduction in these layers competing with the 2DEG.

Later in the program, we focused our effort on growing high-mobility 2-DEG structures which seem to be the most promising for mixer applications. The growth of extremely high mobility semiconductors has traditionally been for scientific interest rather than for device applications. Besides the ultimate goal of achieving the highest mobility, other factors have not been taken seriously into consideration. Most of the high-mobility 2-DEG samples are grown by molecular beam epitaxy (MBE) and include some kind of AlGaAs/GaAs superlattice buffer layers. In a MBE grown structure, the AlGaAs/GaAs buffer has been shown to smooth out the interface roughness of the substrate, as well as to getter impurities (Petroff, 1984). Since aluminum is easily absorbed by a graphite baffle and reactor walls where aluminum oxides can form , it is very effective in removing impurities from the gas stream (Keuch, 1987). Both MBE and OMVPE researchers have used this technique to obtain high-mobility 2DEG structures (Pfeiffer, 1989; Frijlink, 1988). In fact, the sample with the highest mobility ever reported, 11.7×10^6 cm^2/V-s, involved the growth of 220 layers. As a result of the extensive buffering, the samples are extremely light sensitive and the total epi-layer thicknesses are large. The dark mobilities of these samples are typically a fraction of their maximum light values.

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.

Typical 2-DEG structures include a 1.2μm GaAs buffer, a 360Å undoped AlGaAs spacer, a 500Å uniformly doped (mid-1017/cm3) AlGaAs, and a 200Å doped GaAs ($1 \times 10^{18}/cm^3$) contact layer. The Al composition in the AlGaAs layers is about 38%. Preconditioning of the reactor was essentially performing an AlGaAs-related buffer growth without the substrate in the reactor. The temperature was set at 750°C and the reactor was at atmospheric pressure. The sources used were exactly the same as for the device growth run. Two types of pre-runs were experimented with: thick undoped AlGaAs and thick undoped AlGaAs with a three period 500Å/60Å AlGaAs/GaAs multiple quantum wells (MQW). After the pre-run and a 30 minute nitrogen purge, the substrate was loaded and the growth of the 2-DEG structure was performed. Since the reactor does not have a load-lock set-up, a positive nitrogen flow was maintained to minimize exposure of the reactor chamber to air.

To compare the effectiveness of the pre-run with the conventional AlGaAs buffer technique, experiments were performed with the substrates loaded before the pre-run. 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 grown with the pre-runs.

Characterization of the resulting 2-DEG structures was performed by computerized Hall effect measurement using the van der Pauw method. 77K dark mobility measurements were made by cooling the sample in the dark to 77K and measuring the sample in a dark dewar. 77K light mobility measurements were made by initially exposing the sample to intense white light while the sample is being immersed in liquid nitrogen and then placed in a dark chamber for the duration of the measurement. In addition, mobility measurements were performed at liquid helium temperatures for some samples.

A plot of the Hall mobility versus temperature for the best sample is shown in figure 15. Similar to other high-mobility 2-DEGs, the maximum mobility was measured at the lowest temperature, 2.2K, the lowest obtained in our dewar. Other results are summarized in Table 1. Identical growth parameters were used in all the experiments listed except for

SAMPLE	PRE-RUN	LIGHT μ_{77} $cm^2/V\text{-}s$	LIGHT ns_{77} $/cm^2$	DARK μ_{77} $cm^2/V\text{-}s$	DARK ns_{77} $/cm^2$	dark/light μ_{77}
TDEG22	AlGaAs/GaAs	143,000	4.3×10^{11}	105,000	3.2×10^{11}	.73
TDEG23	none	126,000	4.8×10^{11}	105,000	3.5×10^{11}	.83
TDEG24	none	108,000	5.6×10^{11}	65,000	3.6×10^{11}	.60
TDEG31	AlGaAs/GaAs	155,000	4.9×10^{11}	130,000	3.5×10^{11}	.84
TDEG33	AlGaAs/GaAs	171,000	4.7×10^{11}	148,000	3.7×10^{11}	.87
TDEG34	AlGaAs	162,000	4.6×10^{11}	131,000	3.2×10^{11}	.81
TDEG35	AlGaAs	147,000	4.7×10^{11}	128,000	3.3×10^{11}	.87
TDEG39	AlGaAs buffer	143,000	2.4×10^{11}	94,000	1.4×10^{11}	.66
TDEG40	AlGaAs buffer	142,000	2.7×10^{11}	96,000	1.4×10^{11}	.68
TDEG44	SL buffer	166,000	2.0×10^{11}	89,000	8.3×10^{10}	.54
TDEG45	AlGaAs/GaAs	157,000	3.8×10^{11}	113,000	2.1×10^{11}	.72
TDEG48	AlGaAs/GaAs	154,000	3.8×10^{11}	119,000	2.5×10^{11}	.77
TDEG50	AlGaAs/GaAs	153,000	3.9×10^{11}	120,000	2.6×10^{11}	.78

Table 1. Summary of 2DEG experiments

TDEG22 and TDEG23, in which slightly higher silane doping were used. Different arsine sources were used during the course of the study. One surprising result is that variation of the background impurity level of the arsine did not affect the mobility of the 2-DEGs grown by this process, while the mobility of a single GaAs layer is extremely sensitive to this variation (Landini, 1992). Similar high mobility 2-DEGs have been obtained with arsine sources which resulted in GaAs layers with 77K mobility (μ_{77}) ranging from 94,000 to 64,000 cm^2/V-s.

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 (TDEG23, 24). 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 gettering effect of AlGaAs has been known for quite some time, and thus incorporation of AlGaAs-related buffers has become a common practice for high mobility 2DEG growth by both MBE and OMVPE (Abrokwah, 1986; Andre, 1984). Results of our series of experiments indicate that pre-conditioning of the reactor with an AlGaAs-related run essentially yields the same maximum light mobility as those with an AlGaAs or AlGaAs/GaAs buffer. In fact, the sample with the highest mobility (TDEG33) was grown with a pre-run and without an AlGaAs buffer.

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. In addition to greater sensitivity, we also observed carrier trapping effects in the samples with AlGaAs or MQW buffers. During the 77K Hall measurements by the van der Pauw technique, the measured voltages overshot after switching to different contacts and took a few seconds or tens of seconds to stabilize at a lower value. Shining white light on the sample during measurement sometimes helped to reach a steady Hall or resistivity voltage faster. This enhanced carrier trapping and persistent photoconductivity effects in AlGaAs/GaAs devices are well known (Fischer, 1984; Nathan, 1986) and they were related to the DX-centers in the AlGaAs. It is therefore not surprising to see the significant difference between the two kinds of devices since the ones without the AlGaAs buffers have less than 1000Å of AlGaAs in the structure.

The new high mobility wafers will be utilized for further exploration of Mode IIa and IIb mixers. The lower density wafers ($n_s = 4 \times 10^{11}/\text{cm}^2$) should be ideal for fabricating the next generation of devices operating in Mode I. Graduate student Farid Agahi completed a M.S. thesis on the optimization of 2DEG growth by OMVPE (Agahi, 1992).

Integrated Focal Plane Arrays

Our previous work on TSA arrays had typically employed plastic substrates, such as Duroid or Kapton, with fairly low dielectric constant. TSAs are sensitive to the thickness and dielectric constant of the medium along the tapered slot, and we have empirically found that the optimum substrate thickness is given approximately by:

$$t \simeq (0.01 - 0.02) \times \frac{\lambda_o}{\sqrt{\epsilon_r} - 1}, \tag{4}$$

where ϵ_r is the dielectric permittivity of the substrate, and λ_o is the free space wavelength. This means that a silicon or *GaAs* substrate, used for a 1 THz antenna element, should be about 1-2 μm thick. In order to ease the fabrication of such antennas, we have investigated methods for etching the silicon out in the entire region between the metal edges of the tapered slot. This idea was invented in our group, and also independently by Kotthaus & Vowinkel, (1989). We have extended this into a two-step etch process, in which we first etch most of the substrate area from the "back" (un-metalized) side, using a wet etch, and then perform a reactive ion etch (RIE) from the front side, with the TSA metal pattern as the etch mask. These features are illustrated in Figure 15. We have mainly fabricated single elements while developing these processes, but have recently demonstrated a linear seven- element array at 94 GHz, for convenience fed from a waveguide block. A photograph of this array is included as Figure 16. The backside etching in this case left a layer of silicon of about 25 μm thickness. The radiation patterns of an element in this array show very low sidelobes, and low cross-polarized radiation, and could be used to couple an integrated device efficiently to a lens or reflector.

In order to scale the silicon (or $GaAs$) TSA to 1 THz, one would need to produce a substrate thickness of 2-3 μm. This is difficult with our present methods, but could be done in $GaAs$ by growing an etch-stop layer, such as $AlAs$ or $AlGaAs$, in the OMCVD system. Another alternative is to use a silicon-oxynitride membrane, and etch the TSA in a metalized layer deposited on this membrane. The membrane has originally been grown on a silicon substrate, and is about 1.3 μm thick. Ekström et al., (1992) recently demonstrated a TSA fabricated in this manner and tested it with excellent results at 800 GHz. Similar membranes can also be deposited with RIE on $GaAs$, and this technology appears compatible with fabrication of 2DEG devices. The groundwork for designing future focal plane arrays, integrated with 2DEG mixers, thus has been laid.

CONCLUSION

We believe that the work on this IRP has shown the feasibility of a new approach to low-noise THz receivers, based on "bulk" hot electron effects in the 2DEG medium. The specific mode of operation of this mixer as originally proposed has not been possible to implement so far, but a new mode was invented, and experimentally demonstrated. We have increased the bandwidth by three orders-of-magnitude compared with previous hot electron mixers. A number of other elements required for the design of a THz mixer have also been demonstrated, such as monolithic integrated circuit techniques, charge-carrier inertia, improved growth by OMCVD, and an array of TSA elements, etched from a silicon substrate, which can form the basis of future THz focal plane arrays with integrated 2DEG mixers. We believe that the general area of THz applications of bulk effects in the 2DEG medium is a very promising one, as shown by the fact that a new mode of operation was found, when the proposed one turned out to be difficult to implement. Several new effects, such as the Shubnikov-deHaas effect detector, and the detection of an extremely strong and narrow cyclotron resonance line in the Mode I mixer, were also discovered. As a result of the IRP, we are now at a point where a THz 2DEG mixer could be developed, and integrated with an antenna array. Furthermore, several other effects which we discovered in the 2DEG medium appear worthy of continued investigation.

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Yang, J.X. 1992. AlGaAs/GaAs Two Dimensional Electron Gas Devices: Applications in Millimeter Waves and Submillimeter Waves. Ph.D. Thesis, University of Massachusetts @ Amherst, Department of Electrical and Computer Engineering, Sept. 1992.

Theses are also expected to be completed in the near future by Agahi (Ph.D.), Basco (M.Sc.), Dai (M.Sc.) and Li (M.Sc.). They are based, at least in part, on work on this grant.

INVENTION DISCLOSURE

The following invention disclosure was submitted, based on work on this grant:

Yngvesson, K.S., Lau, K.M., and Yang, J.-X. (1989). Nonlinear Two-Dimensional Electron Gas Element for Cryogenic Mixer and Harmonic Generator Applications at Millimeter Waves and Submillimeter Waves. Invention disclosure, the University of Massachusettts @ Amherst, December 5, 1989 (see Appendix).

APPENDIX I:

Invention Disclosure

RESEARCH CORPORATION TECHNOLOGIES

Invention Disclosure Form

I. Description

Please provide a title for your invention and a brief description. Inventions include new processes, products, apparatus, compositions of matter, living organisms—OR improvements to (or new uses for) things that already exist. Use additional sheets and attach descriptive materials to expand answers to questions. (Sketches, drawings, photos, reports and manuscripts will be helpful.)

A. Invention Title Nonlinear two-dimensional electron gas element for cryogenic mixer and harmonic generator applications at millimeter waves and submillimeter waves

B. Description See attachment

C. What are the immediate and/or future applications of the invention?

Cryogenic mixers for millimeter waves with high burn-out power. Harmonic generators with high power handling capability. Future versions may be feasible for submillimeter waves.

D. Why is the invention better—more advantageous—than present technology? What are its novel and unusual features? What problems does it solve?

It can be fabricated with larger area than present devices, and still work up to high frequencies due to much lower parasitic reactances. The high power handling capability follows from the large area.

E. Is work on the invention continuing? Are there limitations to be overcome or other tasks to be done prior to practical application? Are there any test data?

Yes. Test data will be available in the next few months.

F. Have products, apparatus or compositions, etc. actually been made and tested?

Made, but not tested.

II. Publications, Public Use and Sale

Note: valid patent protection depends on accurate answers to the following items.

A. Has invention been disclosed in an abstract, paper, talk, news story or a thesis? No

Type of disclosure ----- Disclosure Date -----
(Please enclose a copy)

II. (Publications, Public Use and Sale—Continued)

B. Is a publication or other disclosure planned in the next six months?

Type of disclosure Conference paper will be written when test data are avail. Date
(Enclose drafts, abstracts, preprints)

C. Has there been any public use or sale of products embodying the invention?

Describe, giving dates No.

D. Are you aware of related developments by others? If "yes," please give citations. Copies of any relevant patents or publications would be appreciated. A related device has been described by Smith et al. (paper enclosed). Their devic achieves its nonlinear characteristic only at much lower temperatures (4 Kelvin) and due to a different physical process.

III. Sponsorship

If the research that led to the invention was sponsored, please fill in the details and attach a copy of the contract or agreement if possible.

A. Government agency NASA contract/grant no. NAGW-1659/5-28908

B. Name of industry, university, foundation or other sponsor:

C. Has the invention been disclosed to industry representatives? If "yes," please provide details, including the names of companies and their representatives.

No.

IV. For Our Records

A. Names and titles of inventors (please print; sign where indicated)

1. K. Sigfrid Yngvesson Signature [signature] Date 12-5-89
2. Kei May Lau Signature [signature] Date 12-5-89
3. J.X. Yang Signature Date

B. Contact for more data K. Sigfrid Yngvesson Tel. (413) 545-0771

C. Mailing address for inventor(s) Department of Electrical & Computer Engineering
University of Massachusetts, Amherst, MA 01003

D. Name and title of institutional representative (please sign where indicated)

Signature Date

Department Tel. ( )

Mailing address

RESEARCH CORPORATION TECHNOLOGIES
6840 East Broadway Boulevard
Tucson, Arizona 85710-2815

Telephone 602/296-6400

APPENDIX II:

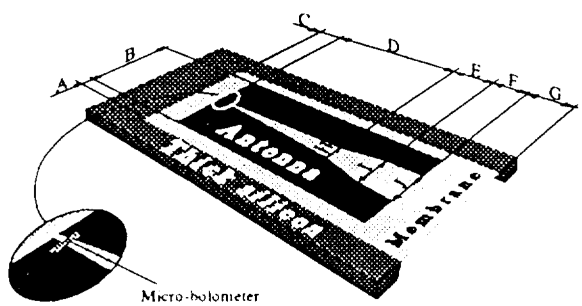
Kollberg et al.: "Hot Electron Mixers: The Potential Competition".

a large dynamic range is required, several long strips can be connected in parallel.

Recently, research in the Electrical Engineering Institute in St. Petersburg has shown that the microwave field in thin film HTS induces a specific non-linear state in the superconductor characterized by zero dc resistance but with considerable losses related to the microwave current (Refs. 18,19). They also showed (in cooperation with H. Chaloupta in Wuppertal, Germany) that this so called "potential-less" resistive state can be used efficiently for low noise microwave mixers. Of great importance for future research is the phenomenological contributions to the understanding of the non linear behavior of the HTS films.

5. HOT-ELECTRON MIXER DESIGN STUDIES

An important basic prerequisite is the recent achievements to realize efficient planar antenna structures for frequencies to above 1 THz. In Fig. 8 is shown a suggested outline for a THz electron bolometric mixer, using either a 2DEG or a superconducting hot electron device. In Fig. 9 we display measured radiation patterns of this type of antenna at 800 GHz, employing a bismuth bolometer (a standard type of bolometer, *not* an electron bolometer). The results indicate that the antenna structure will be useful to at least twice that frequency (Ref. 20).



A = 0.1	B = 1.06	C = 0.1	D = 1.4	E = 0.61
F = 0.56	G = 0.5 - 1	H = 0.14	I = 0.34	J = 0.42

Fig. 8 Slot line antenna structure suggested for an 800 GHz hot electron mixer. The dimensions are in mm.

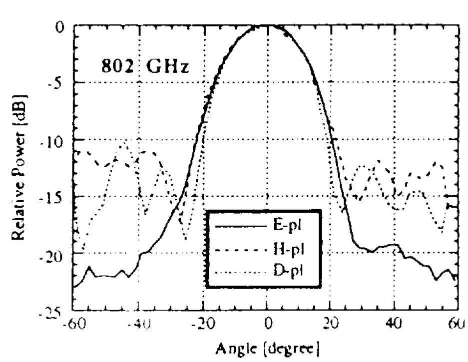


Fig. 9 Measured antenna pattern of an 800 GHz monolithic planar slotline antenna (Ref. 20).

For the 2DEG mixer working in *Mode1* a noise temperature of about 500-1000K DSB is predicted. A superconducting mixer can hopefully do considerably better than this number.

A *Mode2* type 2DEG mixer has not been demonstrated as yet, and may possibly offer considerably lower noise temperatures than the *Mode1* mixer. Notice also that other materials may be available for future research on hot-electron mixers.

6. CONCLUSION

The hot electron mixer seems to be a promising alternative in the race for achieving low noise temperatures in the submillimeter wave frequency range, in particular for frequencies above 500 GHz. However, a lot of work still remains to be done for the final proof of their efficiency in low noise receivers.

7. ACKNOWLEDGEMENTS

The authors are indebted to Dr. J. - X. Yang, Prof. K.-M. Lau, Prof. O. Vendik, and Dr. R. Weikle for valuable discussions and information about their recent work.

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FIGURE CAPTIONS

Figure 1. DSB receiver noise temperatures for different receivers, as a function of frequency. ——- in 1988; - - - - - - in 1992.

Figure 2. Structure of the 2DEG device.

Figure 3. Microwave circuit used in the 94 GHz 2DEG mixer. (Top cover not shown.)

Figure 4. Integrated TSA and 2DEG mixer.

Figure 5. Measured I-V-curves for three 2DEG devices.

(a) MBE Device, $L = 6\mu m$, $W = 100\mu m$, $T_L = 4.2K$;

(b) MBE Device, $L = 5\mu m$, $W = 50\mu m$, $T_L = 19K$;

(c) MOCVD Device, $L = 43\mu m$, $W = 20\mu m$, $T_L = 18K$.

Figure 6. Measured and calculated conversion loss of the 94 GHz 2DEG mixer, as a function of local oscillator power.

Figure 7. Normalized IF response for hot electron mixers.

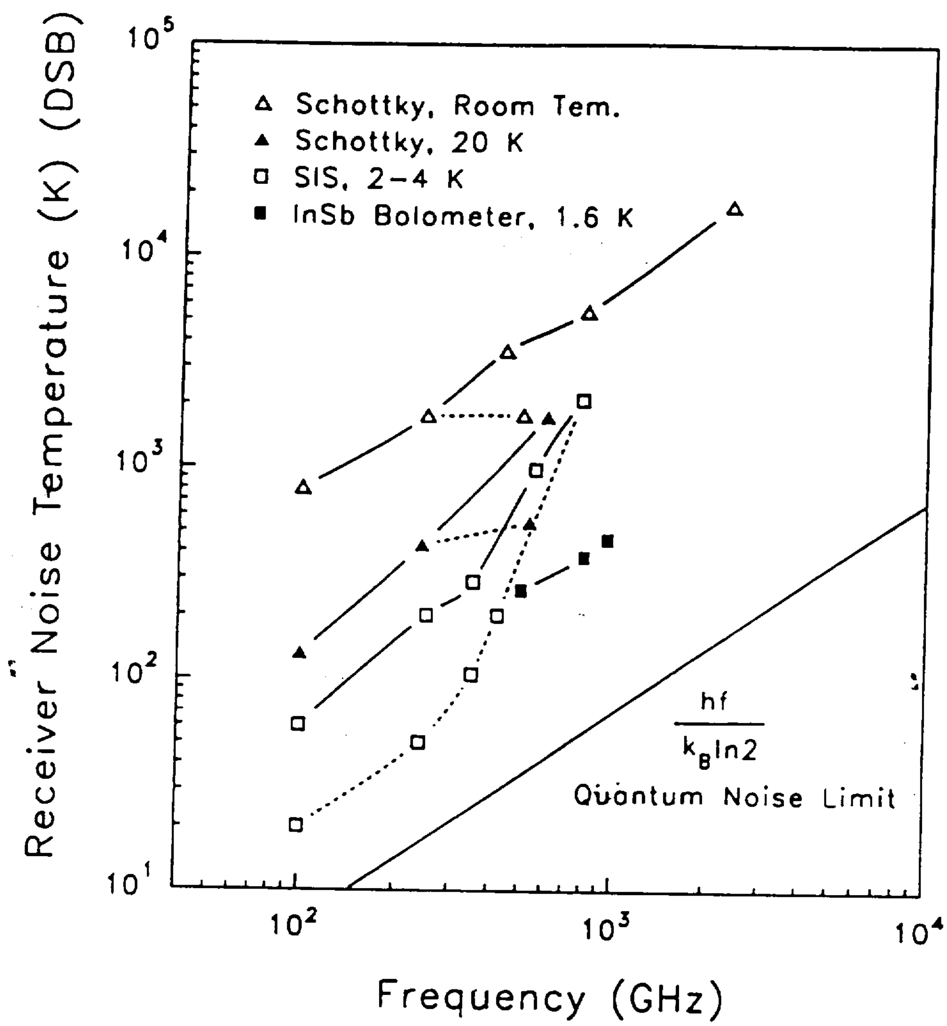
Figure 8. Measured cyclotron resonance detector responsivity at 94 GHz and 238 GHz, respectively.

Figure 9. Conversion loss versus magnetic field under large bias current (4 mA) conditions.

Figure 10. Detected voltage for the *SdH* detector, versus magnetic field. Incident frequencies were 94 GHz and 238 GHz.

Figure 11. Frequency-dependence of the responsivity of the *SdH* detector.

Figure 12. (a) A CPW to slotline balun, fabricated on a silicon substrate. (b) The frequency response of two back-to-back baluns of the type shown in (a). The sharp dip near 17 GHz is an artifact of the measurement setup, not due to the balun.



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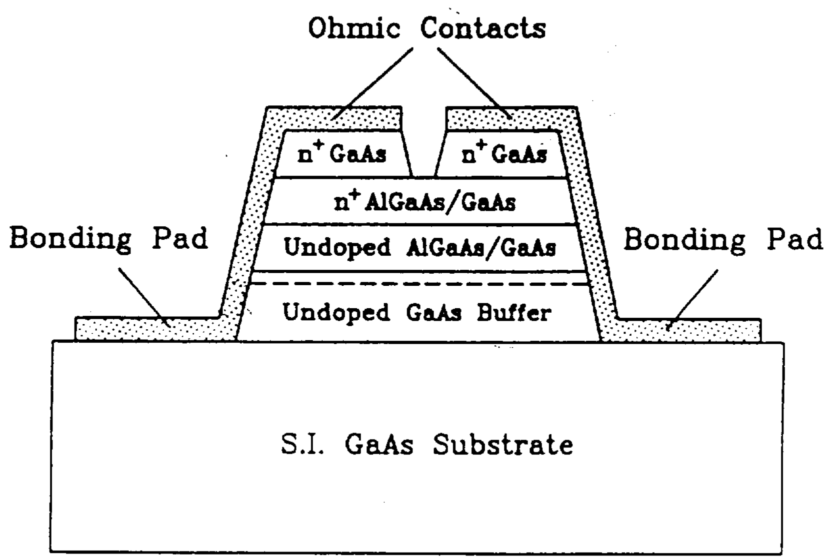

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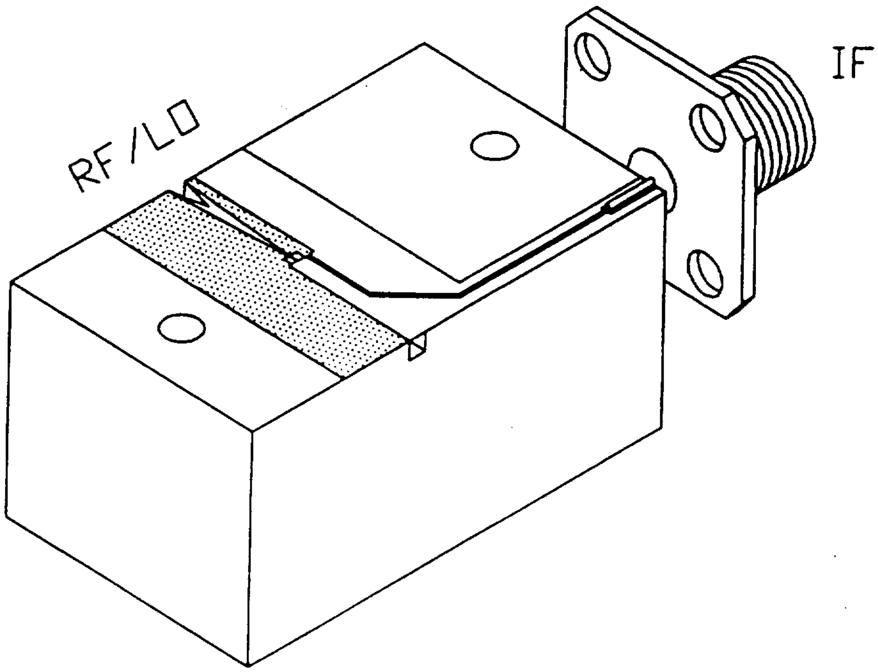

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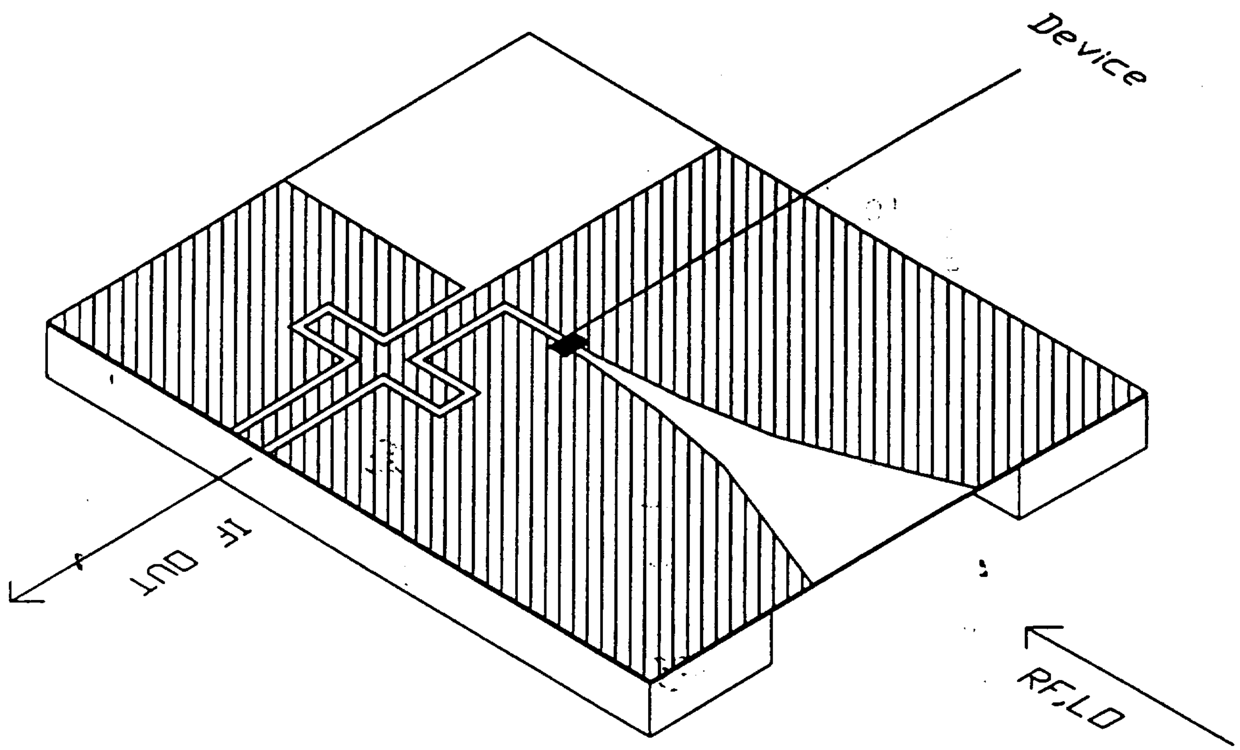
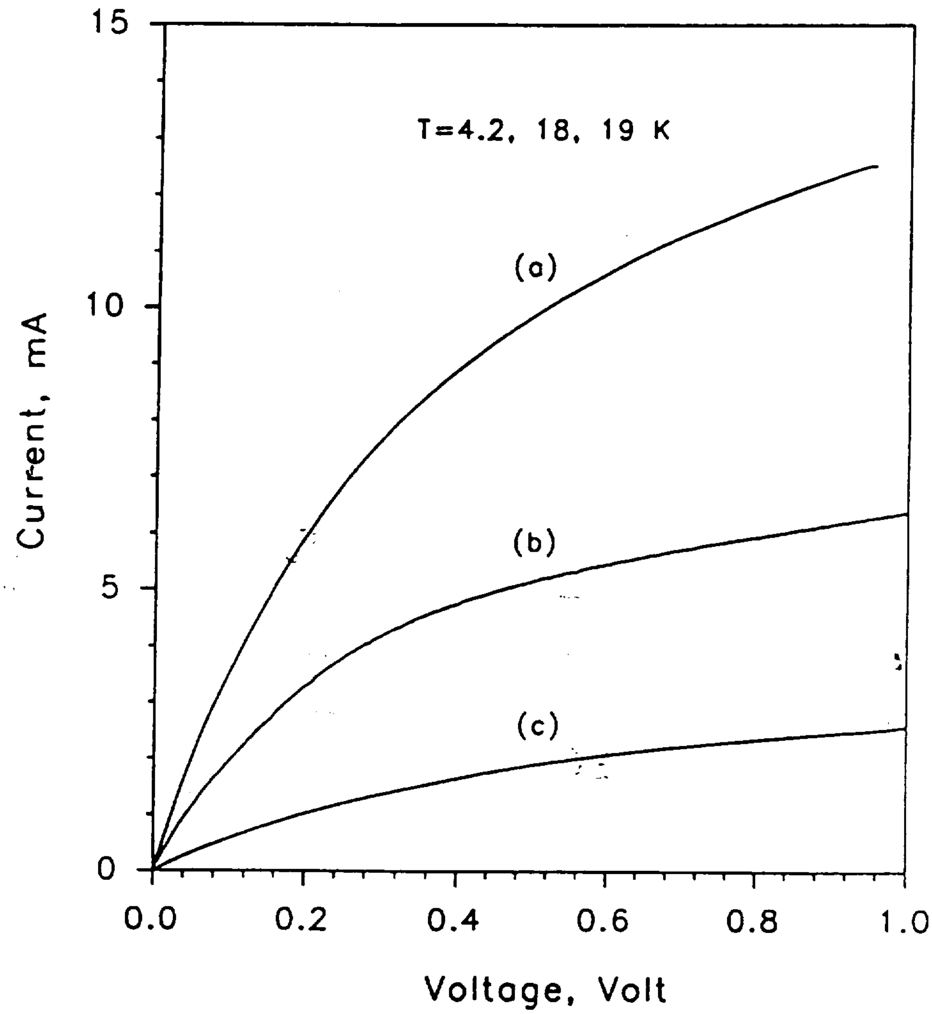


Figure 4. Integrated TSA and 2DEG mixer.



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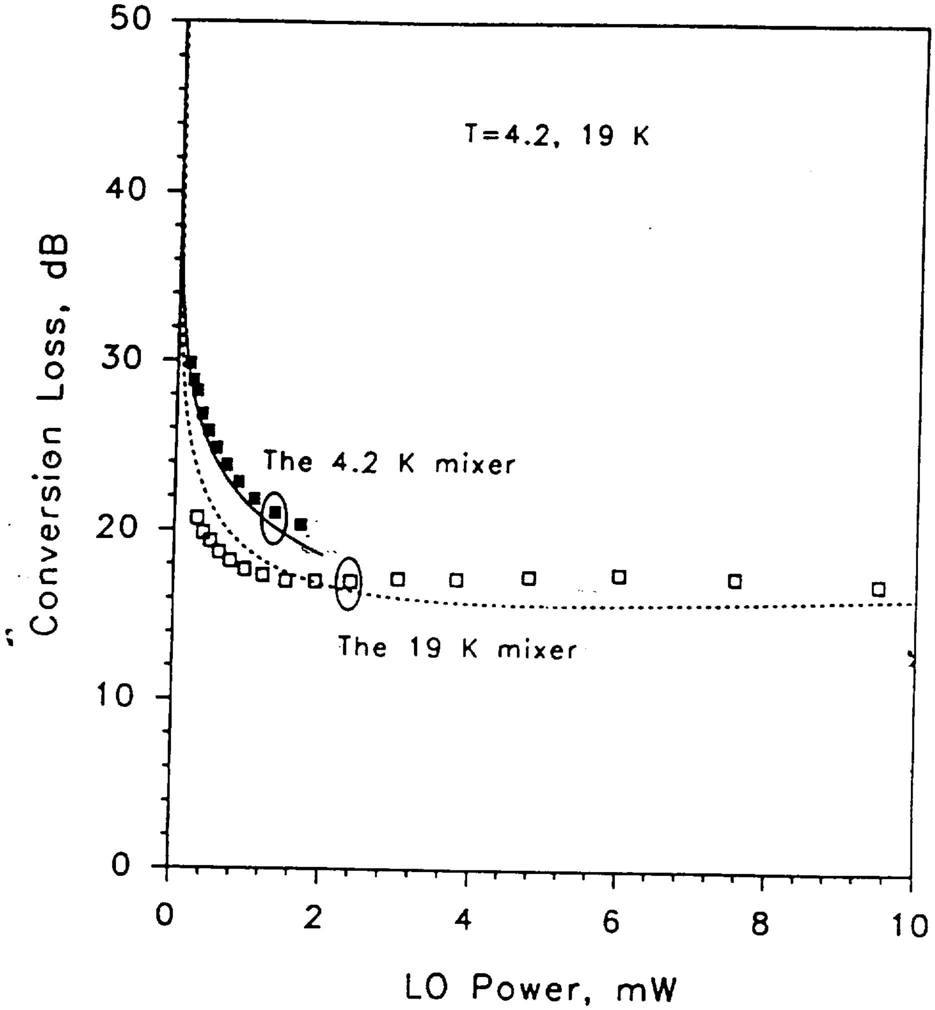

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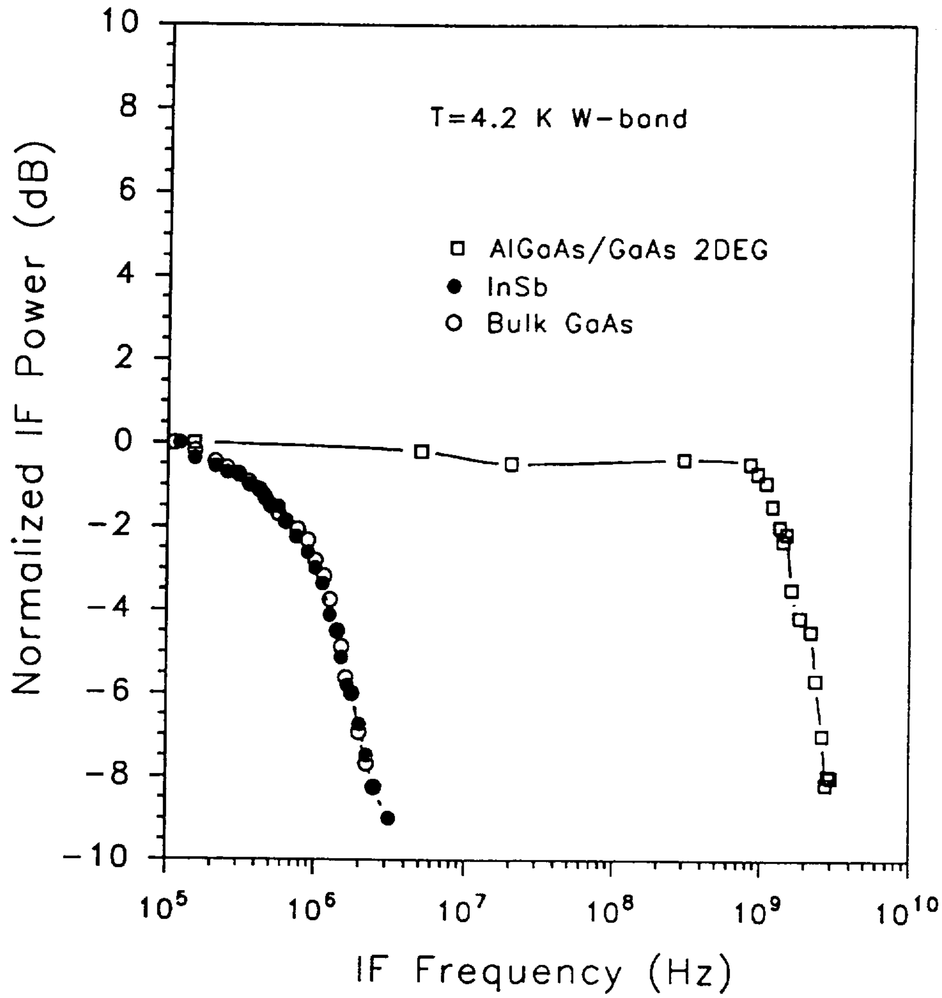
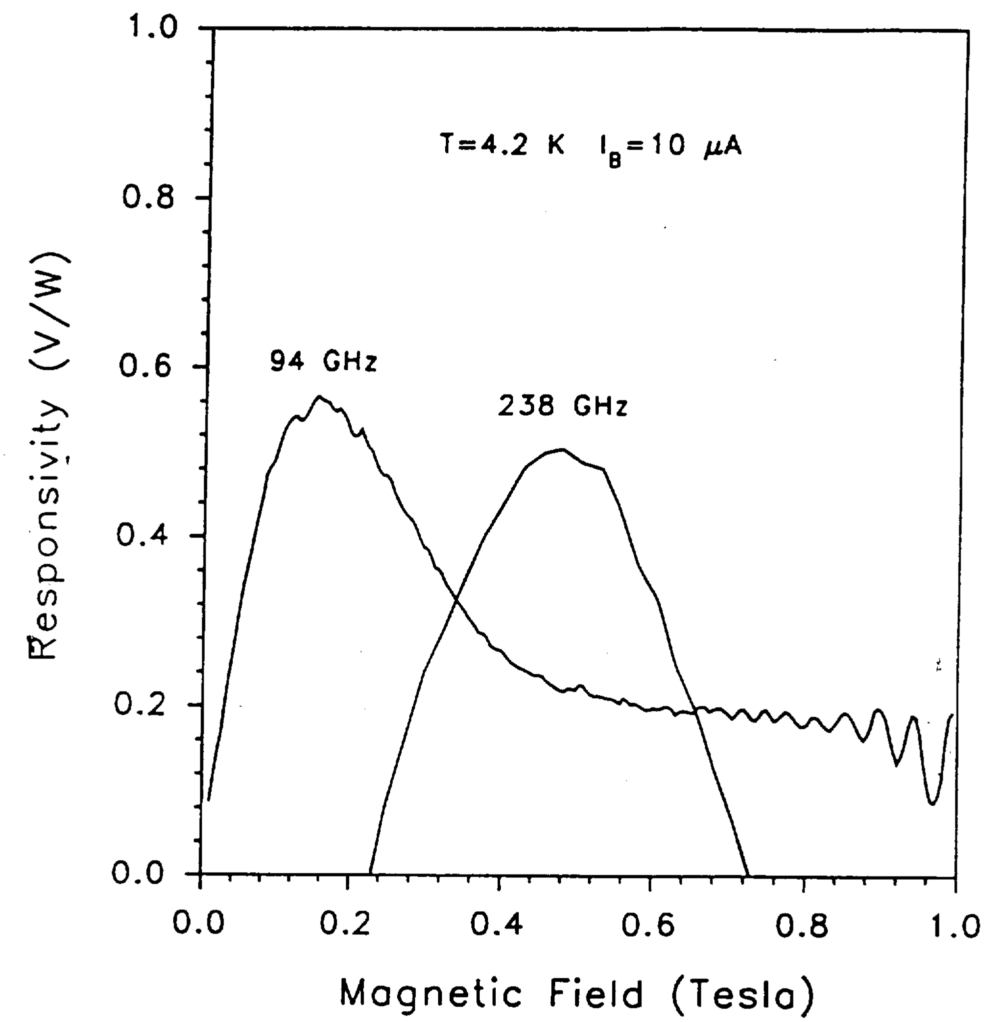


Figure 7. Normalized IF response for hot electron mixers.



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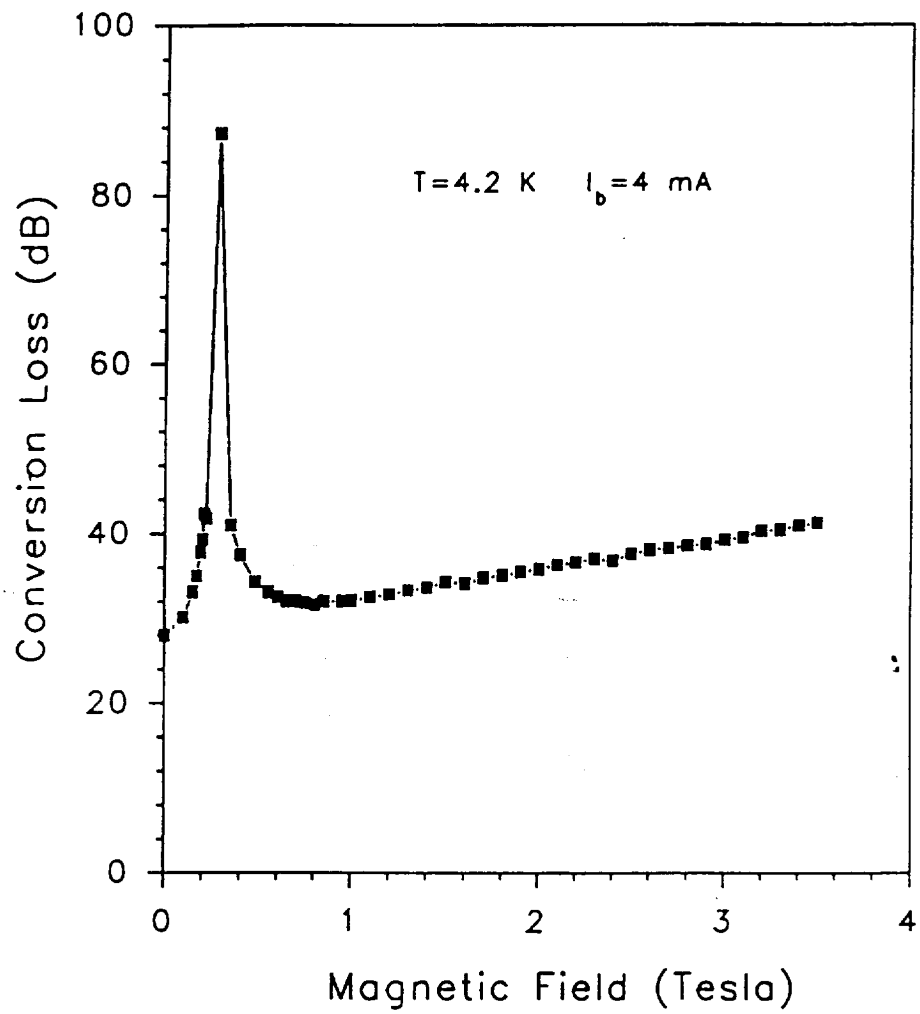


Figure 9. Conversion loss versus magnetic field under large bias current (4 mA) conditions.

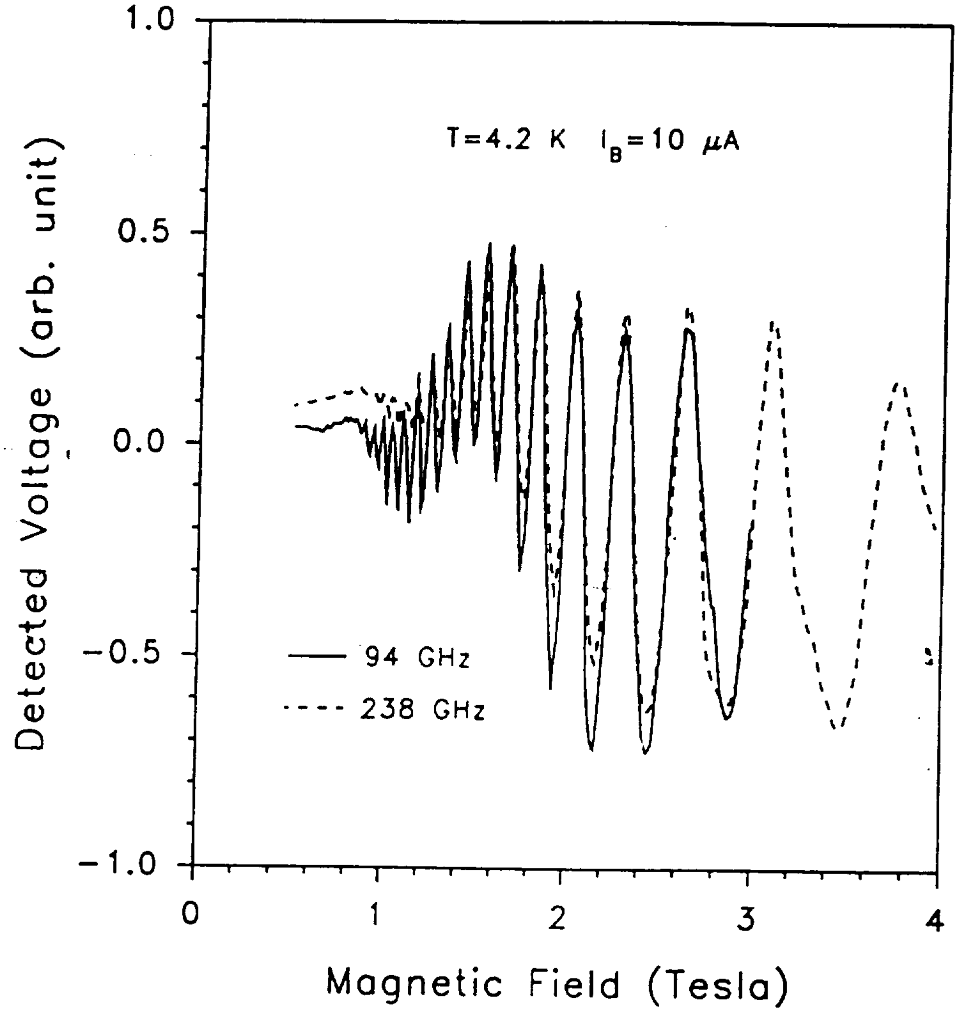


Figure 10. Detected voltage for the *SdH* detector, versus magnetic field. Incident frequencies were 94 GHz and 238 GHz.

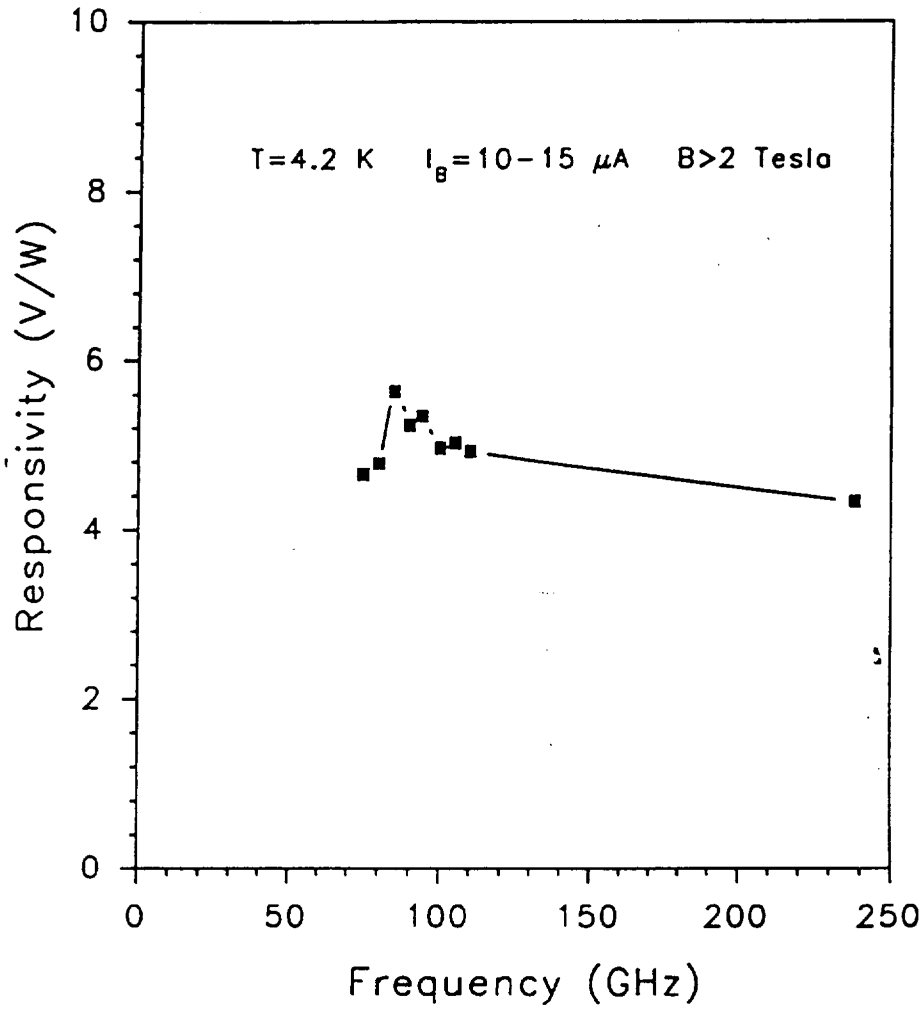
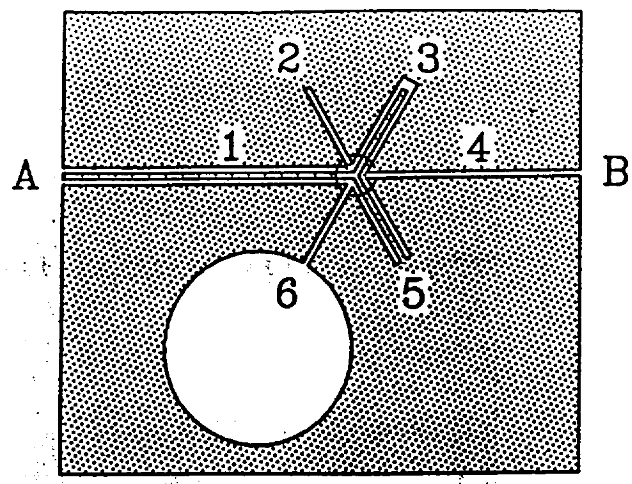
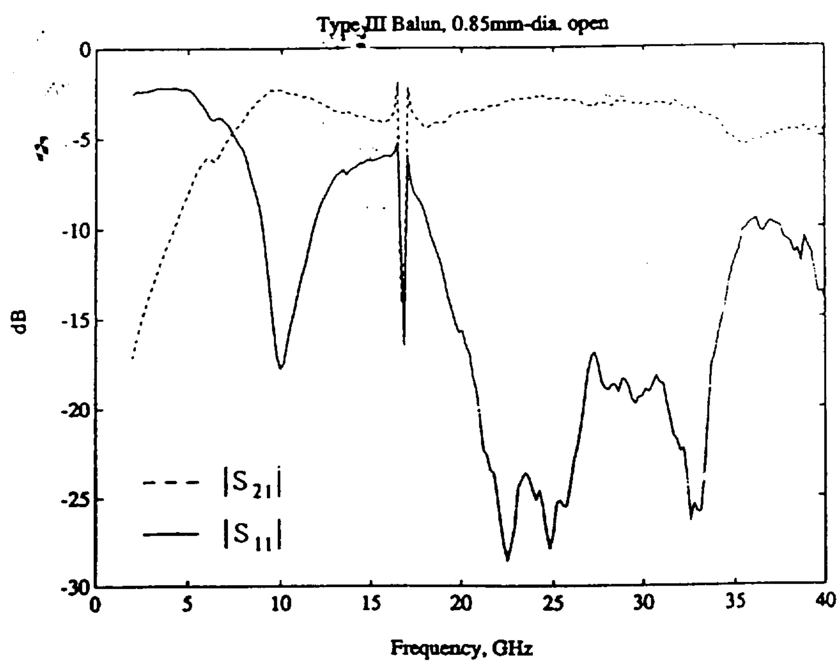


Figure 11. Frequency-dependence of the responsivity of the *SdH* detector.



(a)



(b)

Figure 12. (a) A CPW to slotline balun, fabricated on a silicon substrate. (b) The frequency response of two back-to-back baluns of the type shown in (a). The sharp dip near 17 GHz is an artifact of the measurement setup, not due to the balun.

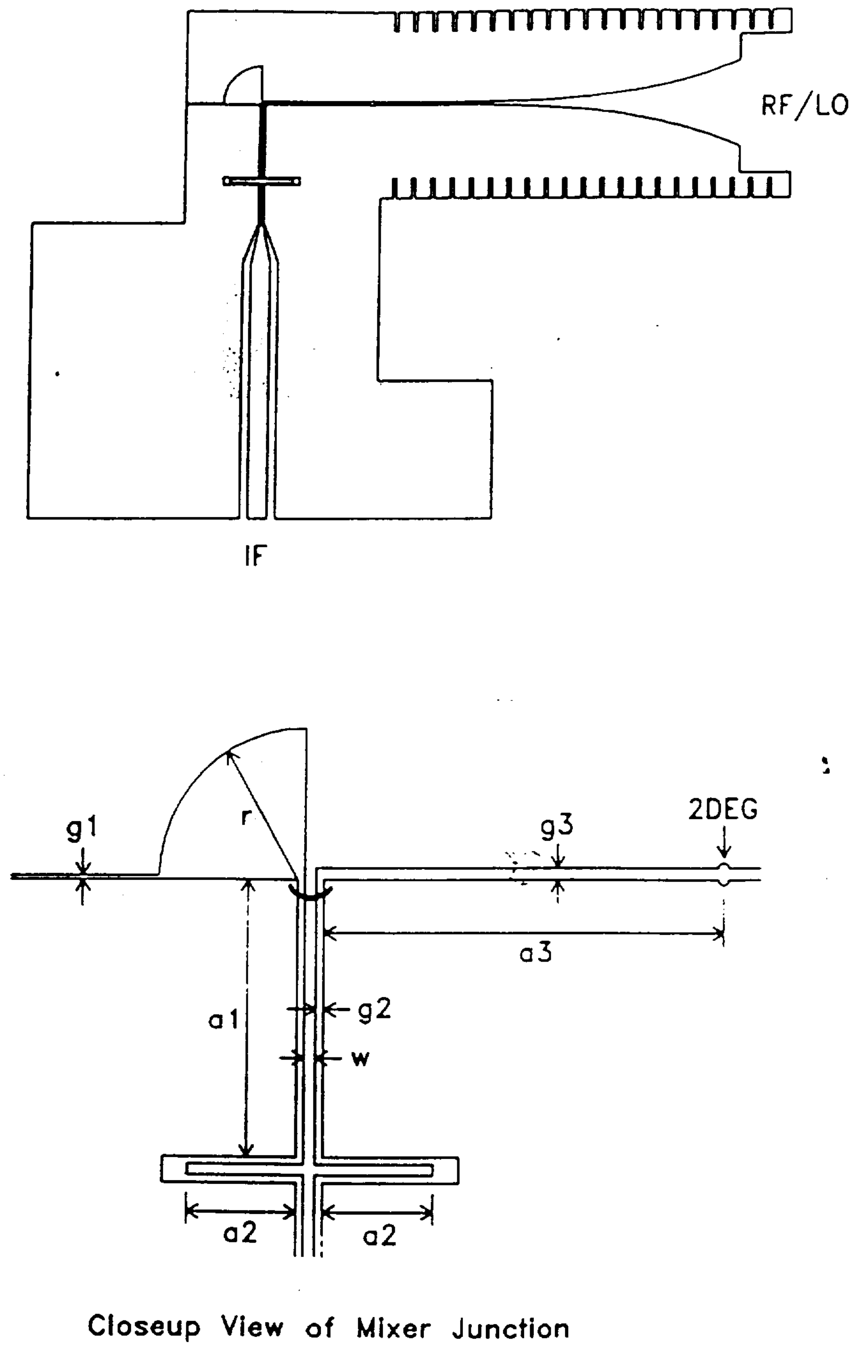


Figure 13. A monolithically compatible mixer circuit, for fabrication on silicon or *GaAs* substrates.

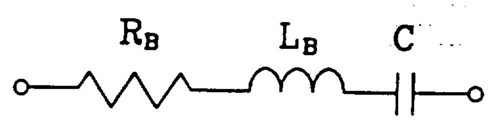


Figure 14. Equivalent circuit of the 2DEG device at high frequencies.

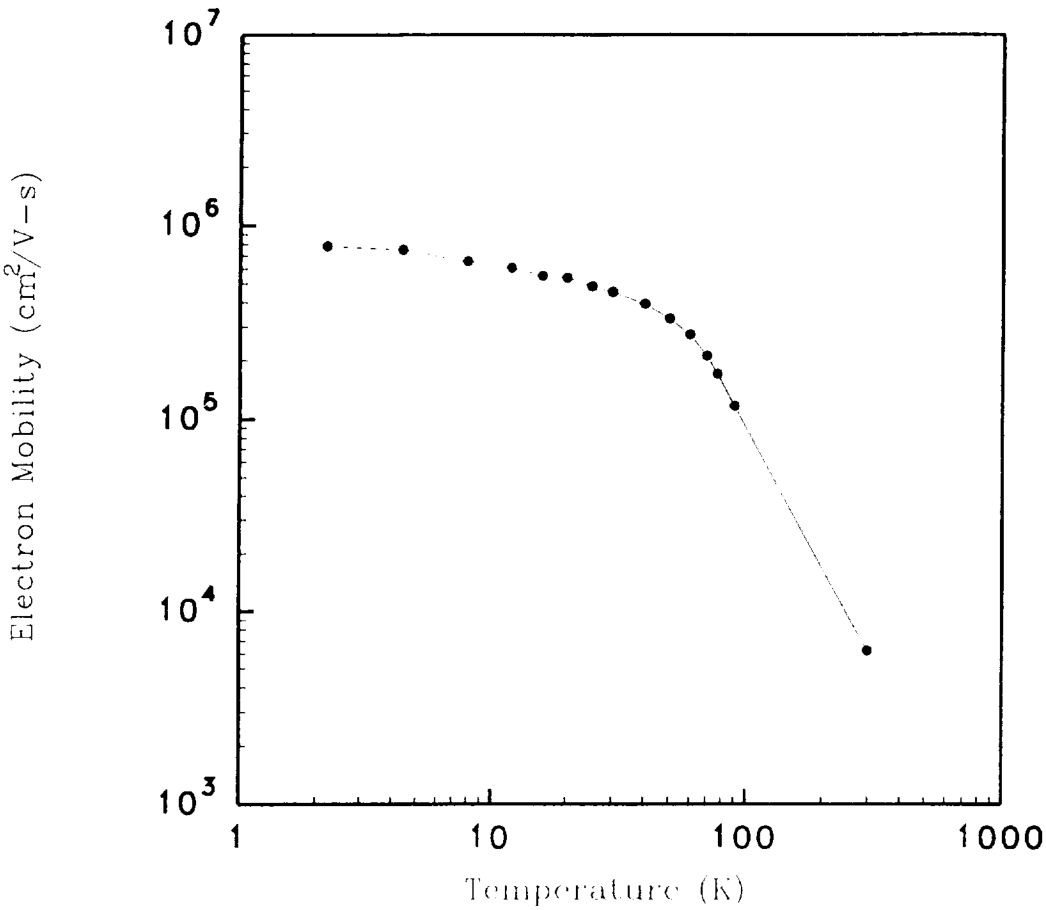


Figure 15. **Hall mobility of the highest mobility sample (TDEG 33) as a function of temperature.**

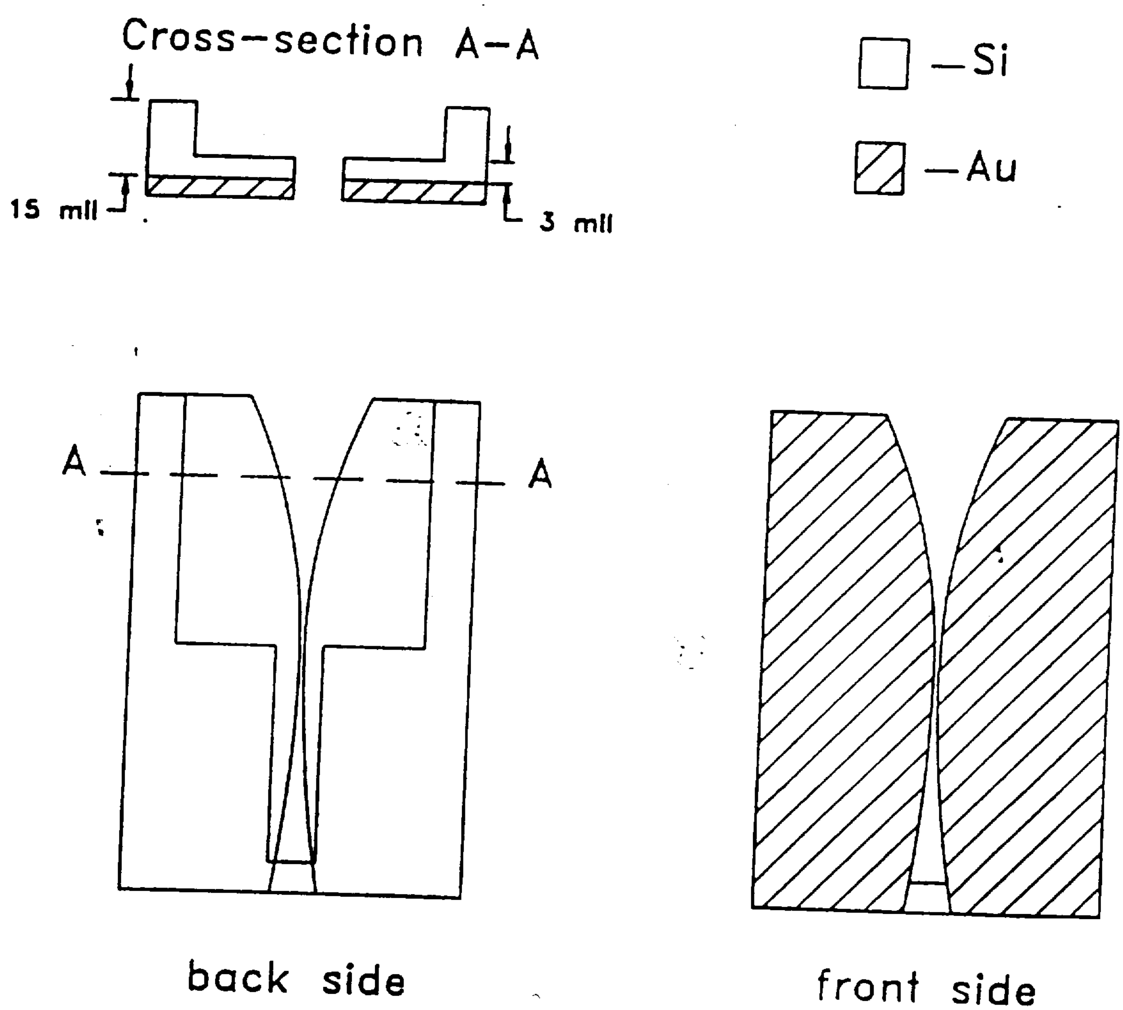


Figure 16. A tapered slot antenna, etched from a silicon substrate.

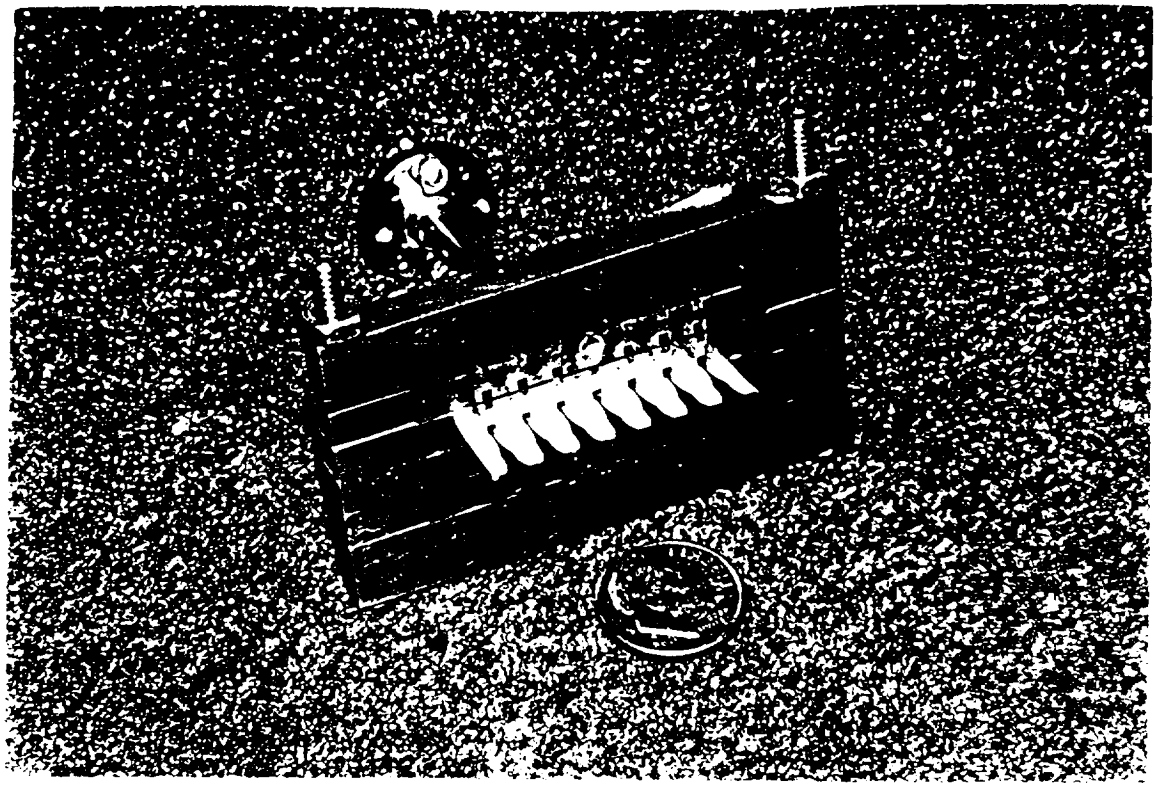


Figure 17. Photograph of a linear TSA array for 94 GHz, etched from a silicon substrate.