The Fabrication and Performance of Planar Doped Barrier Subharmonic Mixer Diodes[*]

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ABSTRACT

The PDB (*P*lanar *D*oped *B*arrier) diode consists of a p^+ doping spike between two intrinsic layers and n^+ ohmic contacts. Such devices can have an anti-symmetric current vs. voltage characteristic. The capacitance is approximately constant with the applied voltage, and the barrier height and device capacitance are easily adjustable. These characteristics make the PDB a candidate for millimeter- and submillimeter-wave subharmonic mixers. We have fabricated a series of 2 and 4 μm diameter diodes with different barrier designs using a GaAs epi-layer. These devices are planarized using an air-bridge and a surface channel etch. After completely removing the substrate, the devices are mounted on quartz substrate to reduce parasitic effects. Diced diodes were tested as subharmonic mixers at 200 GHz in both a quasi-optical planar wideband subharmonic receiver and a planar-diode waveguide-mixer. The results from quasi-optical measurement show that a 0.23 V (and 0.4 V) barrier height GaAs diode with 2.0 μA (and 5 nA) of saturation current gives a DSB conversion loss of 10.8 dB (and 9.5 dB) and a noise temperature of 3795°K (and 2450°K). The results available from waveguide mixers are for a similar 0.23 V barrier height PDB and have a minimum conversion loss improved by 0.6 dB (10.2 dB) and noise temperature reduced by 220°K (3575°K), but required only less than 1 milliwatt of LO power.

1. INTRODUCTION

For space-borne applications, one of the most attractive configurations of submillimeter-wave heterodyne receiver design is the subharmonically-pumped (SHP) mixer. This type of mixer usually requires a device with an anti-symmetrical current-voltage characteristic to be able to perform signal mixing at both positive and negative voltages. Using SHP mixers at over 100 GHz has several advantages. The first is that SHP mixers only require local oscillator (LO) pumping at half of the signal (RF) frequency, which is important because the LO power above 100 GHz

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currently available is small. Other advantages include the simplicity of diplexing as well as the possibility of independent impedance adjustment at the RF and LO frequencies, due to the wide separation of these two frequencies, and the suppression of the local oscillator AM noise [1]. Finally, no DC return path is needed due to zero or near zero DC currents.

The most common device for SHP mixers uses two Schottky diodes connected as an anti-parallel pair to give an anti-symmetrical current-voltage characteristic [2,3]. However, such zero-biased Schottky diode pairs still require a large amount of LO power to sweep over the diodes' turn-on voltage. This limits their usefulness at submillimeter-wave frequencies because currently-used GaAs Schottky diodes have a high barrier height, and thus require large LO power. The absence of biasing reduces the degrees of freedom to adjust differences in the current-voltage characteristics and capacitances between the two diodes of a pair. Such differences cause degradation of mixer performance [4]. To circumvent these problems, recent efforts include the use of low barrier height Schottky diodes from material systems with lower band gaps, or the use of integrated circuit design with bias circuits [5,6]. Another approach is to use Planar Doped Barrier (PDB) diodes with an anti-symmetrical current-voltage characteristic [7], which are discussed in this paper.

PDB diodes were first proposed in 1980 by Malik *et al.* [8]. They employ a thin p^+ layer sandwiched in a lightly doped region to modify potential barriers in semiconductor structures, and two n^+ regions to form the contacts. Such an n^+-i-p^+-i-n^+ structure produces a triangular barrier, and thus charge injection occurs in both directions. By carefully choosing the doping profile and length of i layers, one is able to control the barrier height, capacitance per unit area, space charge resistance, and the degree of asymmetry required in the I-V characteristics. If the p^+ doping spike is placed in the middle of the structure, the current-voltage characteristic can be made anti-symmetric. This type of PDB is a candidate for SHP mixer diode. The benefits of building SHP mixers based on such devices include: (1) a low barrier PDB diode requires lower pump power; (2) the simplicity of the device structure eliminates the occurrence of loop inductance that exists in anti-parallel diode pairs; (3) the balance of the device structure implies a well-matched anti-symmetrical I-V characteristic; (4) unlike Schottky diode pairs, PDB diodes are quite insensitive to surface states and static discharge, and thus, device handling is easier.

In this paper we present a planar fabrication process developed at the University of Michigan for PDB diodes, and their RF performances at 200 GHz in a quasi-optical planar wideband subharmonic receiver at NASA/Center for Space Terahertz Technology [9], and in a planar-diode waveguide-mixer at JPL [10]. Our GaAs PDB #1 has a barrier height of 0.23 V and RF results at both laboratories are presented; GaAs #2 has a 0.4 V barrier height but only the results measured at NASA/CSTT are currently available. The performance results include a conversion loss and noise temperature of 9.5 dB and 2450°K (DSB), measured at NASA/CSTT from PDB #2, and a required LO power less than 1 milliwatt, measured at JPL from PDB #1. Both diodes have very well matched forward and reverse characteristics, with their resulting DC currents in an external loop during the RF measurements less than 10 μA. This is at least an order of magnitude better than that of a typical Schottky anti-parallel diode pair.

The outline of the remaining portion of this paper is as follows. Section 2 describes the device physics and the planar fabrication process. Section 3 gives the device DC parameters and a description of a 91 GHz video detection measurement. The setup and results of subharmonic mixer measurement are presented in Section 4, and finally, conclusions are given in Section 5.

2. DEVICE PHYSICS AND FABRICATION PROCESS

A. Device Physics

An idealized subharmonic planar doped barrier structure is shown in Figure 1. The device designer has control over the material profile and dimensions. The device capacitance per unit area is approximated by the width of the two *i* layers

$$C_{pdb}=\frac{\varepsilon}{2l_i}\ , \tag{1}$$

where $2l_i$ represents the total width of the *i* region, and ε is the semiconductor's dielectric constant. Since the total width of the *i* layer is controlled by the device structure rather than by the bias conditions, the PDB capacitance is approximately constant with the bias. The zero bias barrier height is determined by the combination of the *i*-layer width and the amount of charge in the p^+ doping spike

$$V_{pdb}=\frac{qP_{spike}l_i}{2\varepsilon}\ , \tag{2}$$

where the P_{spike} is the sheet density of charge in the doping spike and q is the electronic charge. A range of barrier heights is possible with proper choice of layer thickness and spike. The charge injection of the triangular barriers can happen in both directions and can be expressed approximately by

$$J_{pdb}=J_0(e^{\frac{qV}{2kT}}-e^{-\frac{qV}{2kT}})\ , \tag{3}$$

and

$$J_0=A*T^2,$$

where V is applied bias, A^* is the Richardson constant, T is temperature, and k is Boltzmann constant.

In a conventional Schottky diode the "ideality factor" is a measure of the physics of the current transport across the barrier. It is near 1 for a good device at temperatures where tunneling current is small. The equivalent "ideality factor" for PDB diodes is at least 2 for either forward or reverse direction. The biased PDB diodes act as a voltage divider, with half of the applied bias appearing across the region to the right of the p^+ doping spike and the other half appearing to the left. This high ideality factor is a potential limitation on the performance of subharmonic PDB mixers.

Space charge resistance is another limitation of PDB devices. In high level injection, the transport carriers screen the electric field, and thus change the shape of the barrier height and affect the current-voltage characteristic. The space charge resistance is approximately proportional to the square of total depletion width and inversely proportional to carriers' saturation velocity. This became a guideline in the design of the second PDB wafer, which cut the space charge resistance by half by reducing the *i*-layer width from 500 Å to 350 Å.

B. Fabrication Process

The device fabrication process for PDB diodes here at the University of Michigan uses an air-bridge and a surface channel etch technique [11,12], modified to include a mesa structure. This process, as shown in Figure 2, is divided into the following nine steps:

(1) Wafer preparation;
(2) Mesa definition and top metallization;
(3) Mesa etch, which uses the ohmic metal as a self-aligned mask;
(4) Bottom ohmic metallization;
(5) Dielectric deposition, which is used for passivation and mechanical support for the coming bridge;
(6) Contact area opening on the dielectric layer;
(7) Thick metal deposition for air-bridge and contact pads;
(8) Channel etch; and
(9) Quartz mounting, and on-wafer test.

If the devices have desirable characteristics, further processing is needed before mounting on RF circuits. One important step is to remove all of the semiconductor substrate, which is lossy at submillimeter-wave frequencies. This is done by a process using wax for protection and support during the substrate etch. The resulting epi-layer only device is subsequently bonded on a 3-mil quartz substrate. The bonding process can be done either via van der Waals force or by UV sensitive glue. The devices on the quartz are diced, and then mounted onto mixer circuits. This quartz stayed on the mixer circuits as our measurements were proceeding; however, if necessary, it can be separated from the GaAs layer by removing the glue between the semiconductor layer and the quartz.

Using the above technique, we have been able to fabricate 2 μm and 4 μm diameter PDB diodes with different layout sizes. A variety of bridge lengths and widths were fabricated to study the optimal design of the bridge. The effect of bridge dimensions on the mixer performance was not seen in the measurements, however, possibly because the system noise had overwhelmed the subtle effects due to the variant bridge dimensions. The sizes of the metal pads for the contacts are either 100x75 μm or 60x30 μm, and are designed to fit in the circuit mount of the planar-diode waveguide-mixer or the planar antenna of the quasi-optical wideband receiver. Figure 3 shows a typical SEM picture of a finished diode, with 2 μm diameter, a 40x2 μm bridge, and two 60x30 μm pads. Figure 4 shows a 2 μm PDB diode, with a 10x2 μm bridge and 100x75 μm pads, flipped over and epoxied on a log-periodic antenna after its substrate is removed and replaced with quartz.

The above process has several advantages. First, the large metal contacts make circuit mounting easy. In comparison to whisker-contacted diodes, planar diodes can reduce assembly cost and improve reliability for space-borne applications. Second, the air-bridge type of interconnection is feasible for submicron devices if the electron-beam writing technique is used for diode definition. Third, the etching of the surface channel and the removal of the semiconductor substrate reduce the parasitic effects and possible losses. Finally, our planar process and device thinning-down technique are ready to be extended to integrated circuit design, but unlike the limitation of MMICs, with a further freedom of choosing adequate substrate material, not necessarily semiconductors.

3. PLANAR DOPED BARRIER DEVICE CHARACTERISTICS

GaAs PDB diodes with different barrier heights were fabricated for mixer measurements. The diced quartz pieces are 250 μm long and 85 μm wide with a 2-μm PDB diode and 100x75 μm of contact pads, plus a variety of bridge dimensions. Diode DC characteristics were measured both before and after diodes were mounted onto the antennas to avoid measuring degraded diodes.

Table 1 shows two sets of diode DC parameters under forward as well as reverse bias, PDB #1 with 0.23 V and PDB #2 with 0.4 V barrier height, both measured with the diodes mounted on the antennas. PDB #1 has a 500 Å *i*-layer, while PDB #2 has a 350 Å *i*-layer, shorter by 150 Å but with a higher p^+l_i product. The design rule employed here is: (1) to increase the barrier height by raising the p^+l_i product, and (2) to decrease the space charge resistance by cutting the *i*-layer width.

The diode capacitance is calculated by the diode nominal anode diameter, 2 μm, and the total depletion width. The diode series resistance (R_s), ideality factor (η), and saturation current (I_s) are all extracted from the measured I-V characteristics by a least squares fitting program. PDB #1 has a zero-bias capacitance of 5.3 fF, an ideality factor of 2.2, a series resistance of 20 Ω, and a saturation current of about 2 μA. PDB #2 has a zero-bias capacitance of 6.6 fF, an ideality factor of 2.7, a series resistance of 14 Ω, and a saturation current about 5 nA.

Two points are important. First, as shown in Figure 5, both PDB diodes have well matched forward and reverse current-voltage characteristics. Second, PDB #2's series resistance is reduced because the space charge resistance is cut by half. The series resistance is the sum the space charge resistance and the contact resistance, which is estimated at 10 Ω from a contact resistivity of 3×10^{-7} Ω-cm^2. Therefore, the space charge resistance is 10 Ω for PDB #1 and 5 Ω for PDB #2.

A 91 GHz video detection measurement was performed to estimate the devices' parasitic capacitance (C_p) of the 20x4 μm bridge PDB diodes. This experiment, as described in [9], is performed by shining a plane wave with a known power density on a log-periodic/substrate lens antenna and by measuring the output voltage across a 106K load. The transmitted power is measured through a 10 dB coupler connected to an Anritsu power meter. The power density on the detector plane can be calculated from this measured power and the distance between the transmitter and detector. The detected voltage across the load is amplified by a Stanford low noise amplifier and read from a lock-in amplifier. The video responsivity defined here is the ratio of the detected voltage to the available RF power of the log-periodic antenna. As shown in Figure 6, the peak video responsivity is about 1300 V/W for a 0.4 V barrier height PDB.

The C_p was estimated by curve-fitting the measured video responsivity. The resulting C_p is about 6 fF for a 20x4 μm bridge PDB. Their RF spreading resistances should be close to their DC values, because the skin effect dominates the current flow in the n^+ region. The theoretical predictions agree reasonably with the measured data except at the higher current region where diodes suffer from the space charge effect.

4. MIXER MEASUREMENT

A. Quasi-optical Measurement Setup

Diode performance was measured at 91-182 GHz in a quasi-optical planar wideband subharmonic receiver by a hot-and-cold load method [9]. This quasi-optical system, shown in Figure 7, consists of four categories of parts: sources, a receiver system, a diplexer, and a lens system. The sources include a 90 GHz Gunn diode as an LO source, whose output power is adjusted by a grid attenuator, and two hot-and-cold sources, made from Eccosorb 72 absorbers with their hot temperature estimated to be room temperature and cold temperature to be 85°K at millimeter-wave frequencies.

The receiver system includes a planar wideband subharmonic mixer and an IF chain. The subharmonic mixer uses a planar self-complementary log-periodic antenna designed to cover the 26 to 260 GHz band, with a PDB diode epoxied at the antenna apex. A silicon lens is placed on the top of the antenna substrate to reduce power loss and improve the pattern and gain. Such an antenna on a silicon lens has a constant input impedance of 74 Ω; it is grounded on one side and on the other side connected to an IF matching network, then an IF chain, and finally a power meter. The IF chain, consisting of a circulator, one low noise amplifier, two second-stage amplifiers, and a 100 MHz band-pass filter, is centered at 1.4 GHz and has a gain of 98.7 dB and a noise temperature of 88.7°K.

Between the sources and receiver is a Martin-Pupplett diplexer, and the lens system. The Martin-Pupplett diplexer is a complex device which contains a beam splitter, made of a 45° grid, and two corner reflectors, one for the transmitted beam and the other for the reflected beam. It is easy to configure the diplexer's path-length difference to allow the maximum LO signal and the upper and lower sideband RF signal at about twice the LO frequency. The lens system includes two lenses and two wire grids. The lenses are 10 cm diameter Rexolite and have to be put at proper places in the beam path, one before and one after the diplexer, for the best coupling of LO signal from the Gunn source to the planar receiver. The RF signal, on the other hand, will be coupled to the hot-and-cold load and pass through only the second lens. A vertical wire grid is placed between the diplexer and the sources to allow only the horizontally polarized RF signal from the RF port or vertically polarized LO signal from the LO port to reach the diplexer. In front of the receiver stands a horizontal wire grid in the 45° plane to reflect the cross-polarized components into a hot-and-cold load. The positions and angles of the grids sensitively affect the signal beam polarization and the occurrence of standing waves.

B. Results of 91-182 GHz Subharmonic Mixer Measurements

Figure 8 shows the measured double-sideband conversion loss and noise temperature versus available LO power at 91-182 GHz subharmonic mixer measurements for PDB #1 and #2. The available LO power for the diode is estimated by measuring the Gunn diode output power and reducing this value by the attenuation factor and system losses, where the system losses include the Gaussian coupling efficiency of the pyramidal LO horn (60%), reflection and dielectric loss of the lens (0.6 dB at 91 GHz and 0.8 dB at 182 GHz), diffraction loss of diplexer (0.2 dB), loss of the silicon lens due to dielectric constant mismatch (1.57 dB), and losses at the antenna system (2.1 dB). The mixer conversion loss and noise temperature take into account diode intrinsic conversion loss, assuming an IF match, and antenna system loss, due to imperfect antenna coupling, residue reflection, and absorption of the silicon lens. The DSB results at 182 GHz have a minimum conversion loss of 10.8 dB and a noise temperature of 3750°K for PDB #1, and 9.5 dB and 2450°K for PDB #2. The LO power for the minimum conversion loss is estimated at 2.2 mW for PDB #1 and 2.7 mW for PDB #2. These results are summarized in Table 2.

Also shown in Table 2 is a result measured in JPL's planar-diode waveguide-mixer at 210 GHz for PDB #1. The DSB minimum conversion loss is 10.2 dB and the noise temperature is 3575°K. These are slightly better than those measured at NASA/CSTT, but the required LO power around 1 mW is lower, which implies that the RF match at the LO frequency at the planar-diode waveguide-mixer is better than in the antenna system. The LO efficiency can be improved by adding a RF matching network at the antenna apex, but at the expense of bandwidth.

5. CONCLUSION

In this paper, we presented the design, fabrication and measurement of GaAs PDB diodes at 200 GHz. The devices' barrier height is controlled by the product of the p^+ sheet charge doping and the intrinsic width, and the space charge resistance can be reduced by shortening the depletion region width. Diodes with 0.23 V and 0.4 V barrier height are fabricated by a planar process using an air-bridge interconnection and surface channel etching to reduce the parasitic capacitance, and further thinning the substrate and mounting on quartz to reduce losses. This process can be easily modified to make integrated receivers with a choice of substrate for THz applications. The devices have a very good anti-symmetry in current-voltage characteristics; the measured diodes show an excellent balance and the external DC loop current seen in the RF measurement is less than 10 μA, an order of magnitude less than that of a typical anti-parallel Schottky diode pair. The PDB performances are evaluated on a quasi-optical planar wideband subharmonic receiver at 182 GHz, which gives a DSB conversion loss improvement of 1 dB and noise temperature reduction of 1300°K as the diode barrier height increases from 0.23 V to 0.4 V. Also presented are the results of the 0.23 V barrier PDB measured at JPL's planar-diode waveguide-mixer at 210 GHz, which show a 1 mW of required LO power at minimum conversion loss. This implies that a more efficient LO coupling in the quasi-optical receiver system is possible by adding an RF matching network at LO frequency at the antenna apex.

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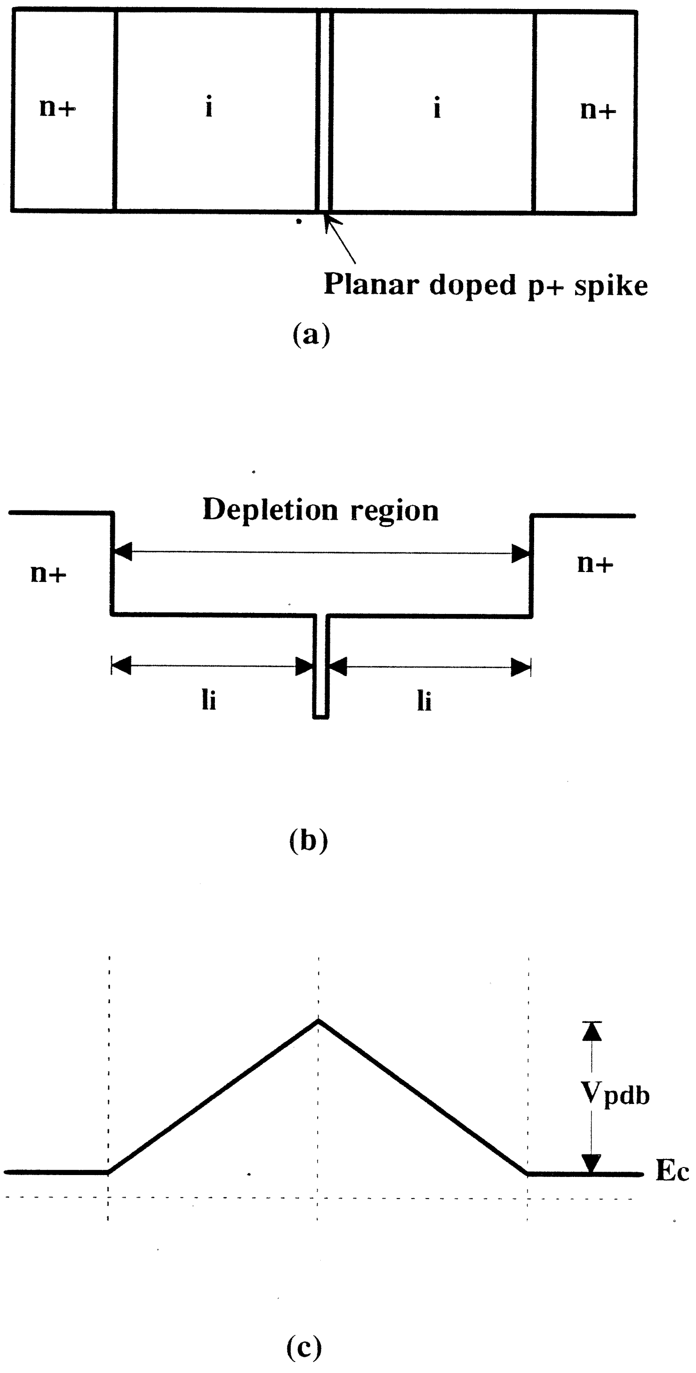


Figure 1: Planar Doped Barrier diodes include a planar doped p^+ spike sandwiched in two intrinsic regions and contact regions (a). They have a constant depletion width (b) and a triangular potential barrier (c).

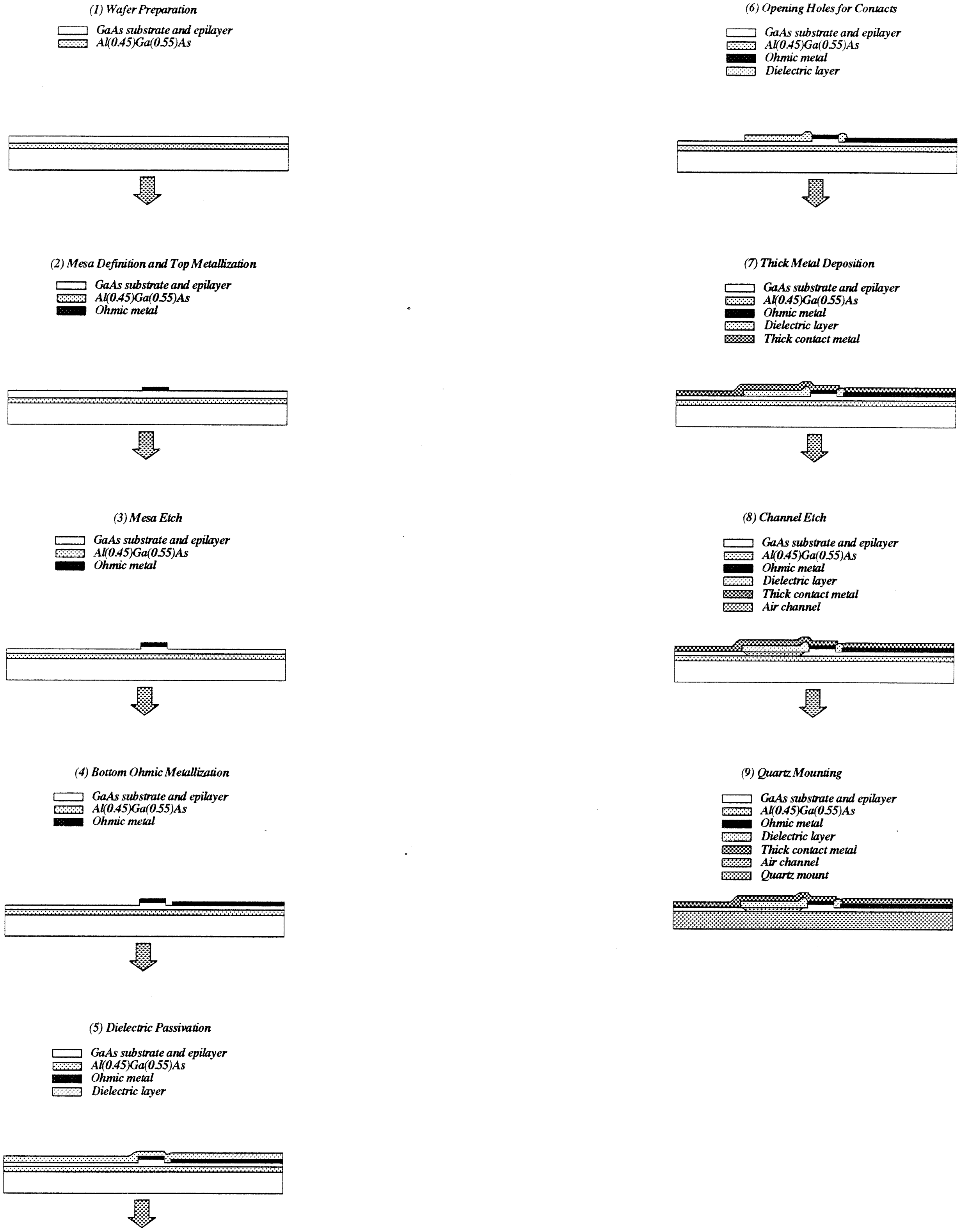


Figure 2: The planar fabrication process for GaAs PDBs using air-bridges, surface channel etching, substrate removing, and quartz mounting techniques.

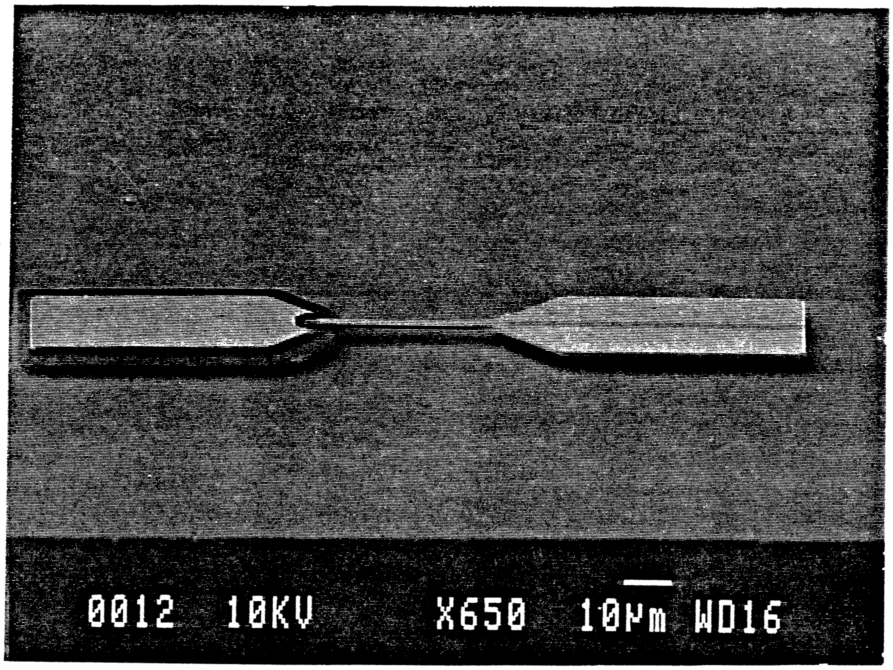


Figure 3: A PDB diode with 2 µm diameter, a 40x2 µm air-bridge, and two 30x60 µm contact pads after channel etch.

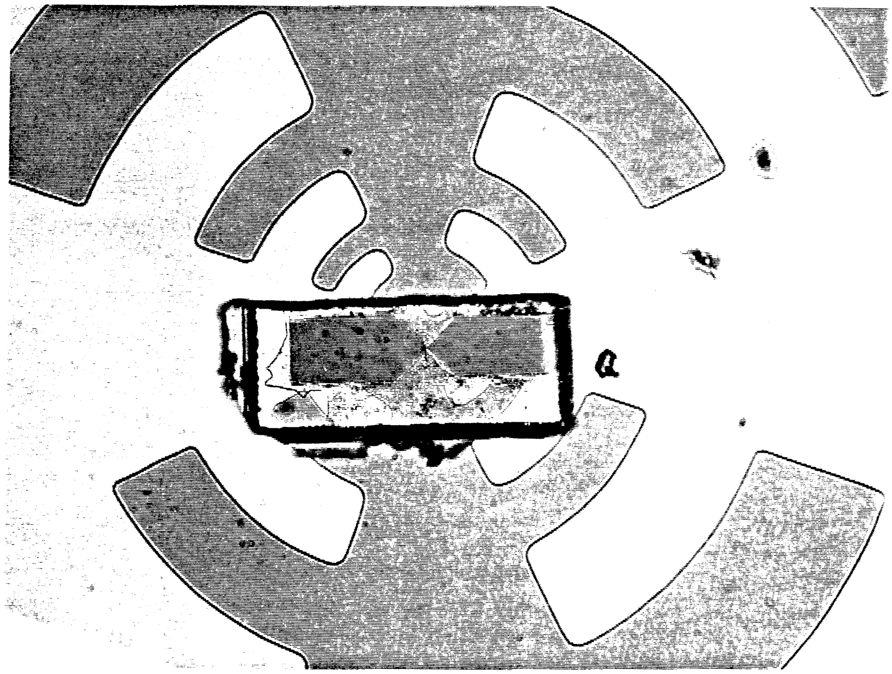


Figure 4: A PDB diode, after thinning and quartz mounting, flipped over and epoxied on a log-periodic antenna.

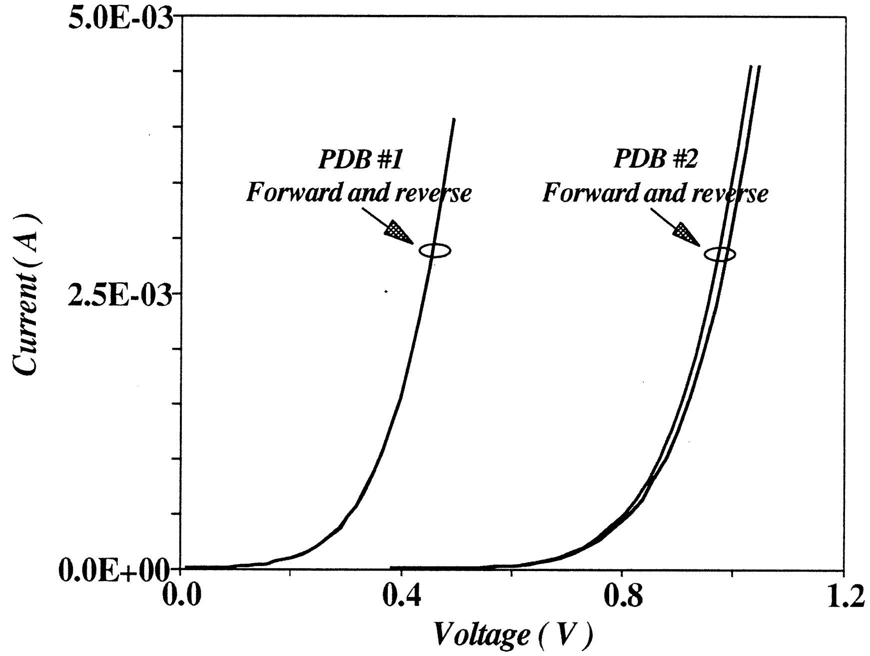


Figure 5: Current-voltage characteristics for two 2 μm GaAs PDBs.

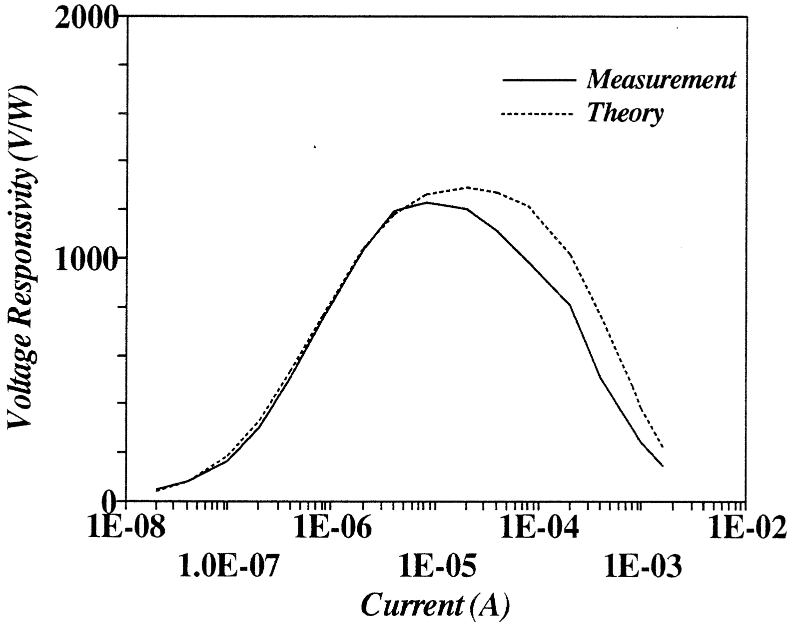


Figure 6: Video responsivity of a 0.4 V barrier height PDB at 91 GHz.

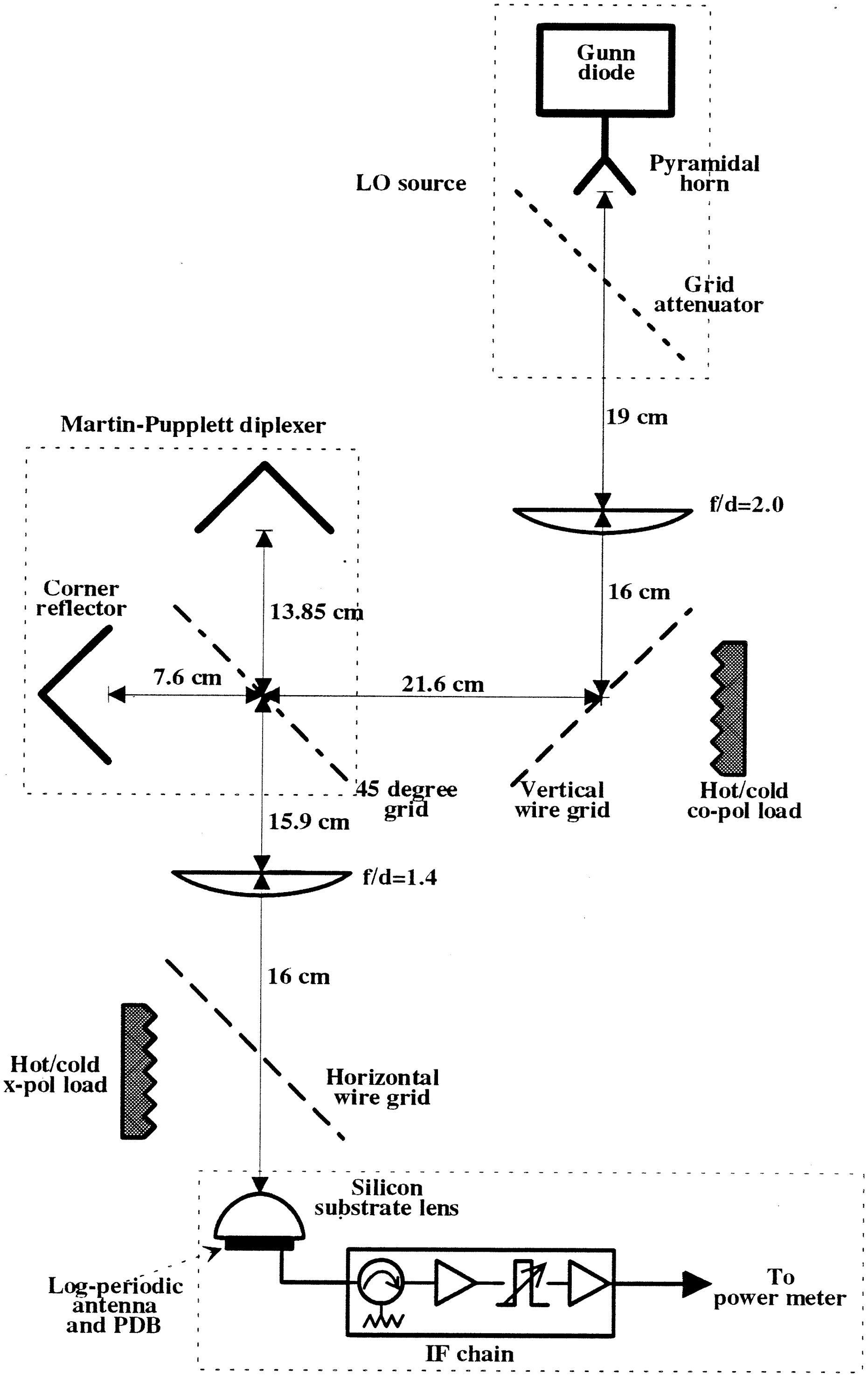
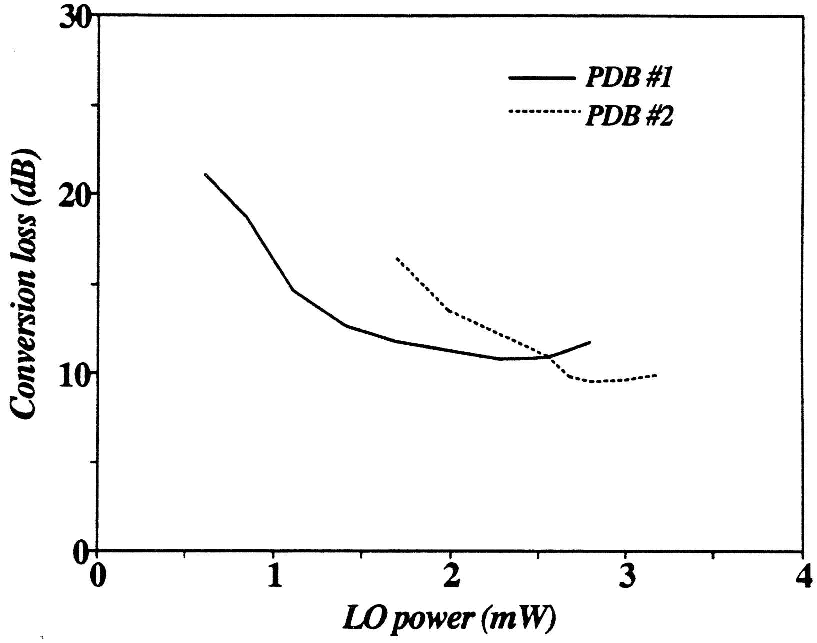
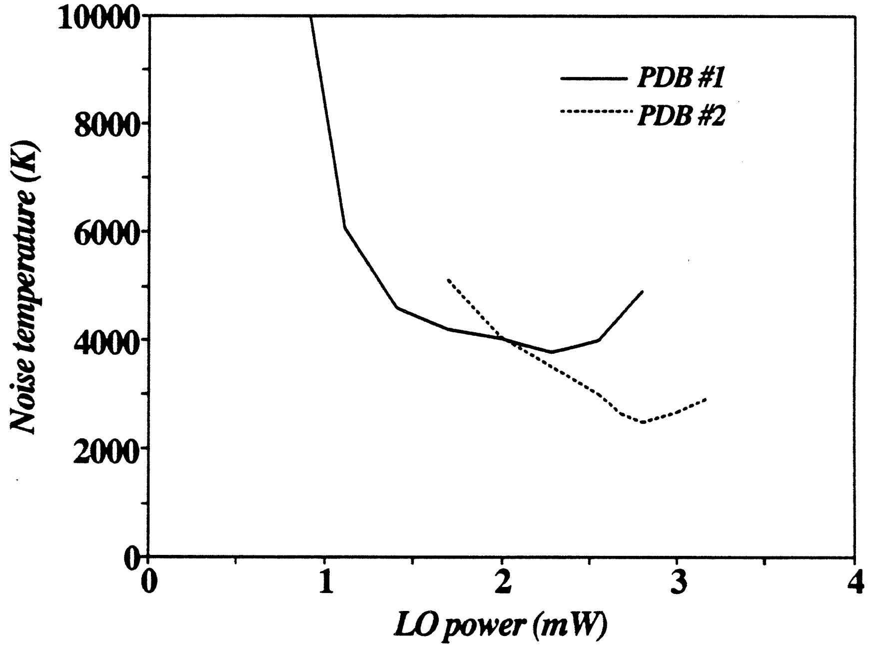


Figure 7: Mixer measurement setup of a quasi-optical planar wideband subharmonic receiver at UM NASA/CSTT.



(a)



(b)

Figure 8: The diode conversion loss (a) and noise temperature (b) versus estimated LO power in the quasi-optical receiver system for PDB #1 and PDB #2.

Description	C_{j0} fF	ϕ_b V	η	R_s Ω	I_{sat} A	Anode Diam.	Finger Length	Finger Width
#1: MBE GaAs from QED - on 3 mil quartz	5.3	.245 .234	2.2 2.2	20. 20.	2.0×10^{-6} 2.0×10^{-6}	2 μm	20 μm	4 μm
#1: Same as the above	5.3	.245 .234	2.01 2.02	20.4 20.3	1.8×10^{-6} 1.9×10^{-6}	2	20	4
#2: MBE GaAs from UM - on 3 mil quartz	6.6	.398 .394	2.71 2.72	14.6 12.6	4.7×10^{-9} 5.4×10^{-9}	2	20	4

Table 1: Device parameters of PDB diodes for subharmonic mixer measurements. Note that: (1) junction capacitance is calculated from nominal anode area and total depletion width, and (2) other parameters are calculated from measured I-V data. Both forward and reverse parameters are shown.

SHP Mixer type	Diode	Frequency (GHz)	DSB T_{mixer} (°K)	DSB Loss (dB)	LO Power (mW)
JPL Planar-diode Waveguide-mixer	#1	210	3575	10.2	1.2
UM NASA/CSTT Planar Wideband Subharmonic Receiver	#1	182	3795	10.8	2.2
UM NASA/CSTT Planar Wideband Subharmonic Receiver	#2	182	2450	9.5	2.7

Table 2: Device performance at 200 GHz Subharmonic Mixer Measurements.