Planar Doped Barrier Subharmonic Mixers*

T. H. Lee, J. R. East and G. I. Haddad

Center for Space Terahertz Technology
The University of Michigan
Ann Arbor, Michigan

Abstract

The PDB (Planar Doped Barrier) diode is a device consisting of a p^+ doping spike between two intrinsic layers and n^+ ohmic contacts. This device has the advantages of controllable barrier height, diode capacitance and forward to reverse current ratio. A symmetrically designed PDB has an anti-symmetric current vs. voltage characteristic and is ideal for use as millimeter wave subharmonic mixers. We have fabricated such devices with barrier heights of 0.3, 0.5 and 0.7 volts from GaAs and InGaAs using a multijunction honeycomb structure with junction diameters between one and ten microns. Initial RF measurements are encouraging. The 0.7 volt barrier height 4 micron GaAs devices were tested as subharmonic mixers at 202 Ghz with an IF frequency of 1 GHz and had 18 dB of conversion loss. The estimated mismatch loss was 7 dB and was due to higher diode capacitance. The LO frequency was 100.5 GHz and the pump power was 8 mW.

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I. Introduction

Planar Doped Barrier devices were first proposed in 1980 by Malik *et al*[1]. The structure can be understood as a planar doped p^+ spike sandwiched between two lightly doped regions and heavily doped n-type ohmic contacts. Such an n^+-i-p^+-i-n^+ device has a triangular potential barrier which is adjustable by the parameters of epi-layer growth such as sheet charge doping density and intrinsic layer dimensions. The devices are unipolar and the charge transport over the potential barrier can be modeled by the thermionic emission theory. The current vs. voltage characteristic is similar to that of Schottky diodes. Accordingly PDB's can be used as a Schottky barrier diode replacement with the additional advantage of barrier height control.

The major applications of PDB devices are as mixers and detectors. If the device structure is designed symmetrically with the p^+ doping spike in the middle of the intrinsic region, the PDB diode has an anti-symmetrical I-V characteristics and is ideal for millimeter-wave subharmonic mixer applications. A summary of the theory and design techniques for symmetric PDB diodes as subharmonic mixers is given by Lee *et al*[2]. Several subharmonic PDB diodes operating at microwave frequencies have been reported[3.4,5]. Güttich *et al.* measured a D-band silicon PDB subharmonic mixer with a minimum conversion loss of 10.8 dB[6]. The structure can also be designed to have lightly doped regions of different thickness. This will provide a current vs. voltage characteristic that is useful in low barrier detectors applications. Dale *et al*[7,8]. reported a PDB single-ended mixer had a noise figure of approximately 6 dB at 9.4 GHz and required only 280 μW of local oscillator power. When used as video detectors, Anand *et al*[9]. showed zero bias PDBs for low level detection had a burnout limit comparable to high barrier Schottky diodes and were less sensitive to the electrostatic discharge.

PDB devices suffer from several problems. The space charge resistance is relatively high. By making the i-layer as short as possible we are able to reduce the space charge resistance. However, the i-layer width has to be larger than the Debye length of n^+ region to avoid the charge redistribution at i-n^+ interface. For a subharmonic PDB diode the ideality factor is at least two. The conversion ability is thus degraded. A careful design is necessary to obtain an optimum performance.

In this paper we present a group of MBE grown GaAs wafers with a 250Å i-layer thickness and the p^+ spike doping densities of 1.5, 2.0 and $2.5\text{x}10^{12}$ cm^{-2} for mixer operation. The barrier height was designed for 0.3, 0.5 and 0.7 volts respectively. The impurity concentration of the intrinsic region is nominally less than 10^{14} cm^{-3}. Also presented are a group of InGaAs wafers grown via gas MBE at the University of Michigan. These wafers are of the same specifications as the GaAs ones except with longer n^+ layers. A preliminary RF result is reported.

II. Fabrication of Whisker-contact Subharmonic PDB Diodes

Two material systems have been chosen: GaAs and InGaAs. The use of GaAs has some advantages. GaAs is a more mature fabrication technology and tight parameter control of MBE grown GaAs is relatively easy. InGaAs, however, has a higher electron mobility and much lower contact resistivity than GaAs. For terahertz operation InGaAs might be a better material system. In this paper, we present diodes from both material systems.

A typical wafer structure for the subharmonic GaAs PDB is shown in Fig. 1. An optimum structure for small diameter whisker-contact PDB diodes with low series resistance and parasitic capacitance is achieved by completely removing the substrate and forming mesas. An etch stop layer of AlGaAs between the substrate and epi-layer was included for this substrate removal. A good selectivity between the substrate and etch stop layer is possible. In the InGaAs system hydrochloric acid was used to remove the InP substrate without affecting the InGaAs epi-layer.

The fabrication of whisker-contact PDB diodes consists of seven major steps as shown in Fig. 2:

(1) diode definition and metallization,

(2) mesa etch,

(3) SiO_2 passivation,
(4) opening contact holes,
(5) front side protection,
(6) backside thinning,
(7) final metallization and plating.

More details on the process steps are given in the next section.

The first step is diode definition and metallization. An image reversal photolithography process was characterized to attain desired diode patterns for ohmic metal lift-off. A positive photoresist was spun uniformly on the wafers, and then soft-baked at 105°C and UV exposed in the conventional way. Next a reversal bake and flood exposure altered the polarity of the solubility of photoresist in the images and fields, so that a negative image could be obtained after development. The exposure and bake parameters are optimized to obtain an undercut profile desirable for the lift-off.

Metallization was then performed by depositing layers of thin film metals on the photoresist patterned samples. Ni/Ge/Au/Ti/Au were evaporated in sequence. The metal covered wafers were soaked in the acetone for lift-off. The resulting dot-like patterns also served as a self-aligned mask for mesa etch.

The next step is the mesa etch. To avoid serious undercut we used a dry plasma etch instead of a wet chemical etch. Mesa etching was accomplished by a reactive-ion etching system. The GaAs wafers were etched in a low pressure chamber filled with BCl_3 and Ar gaseous plasmas of 11:9 ratio to obtain highly anisotropic sidewalls, while InGaAs wafers were etched by the mix of methane, hydrogen, and argon. The effective area of diodes was determined by the area of the p^+ doping spike. With plasma etching the precise control of device area is possible. The desired etch depth is into the first few hundred Å of the bottom n^+ layer. Sometimes a subsequent slow wet etch is used to remove a thin damaged layer.

The third step is SiO_2 deposition. After the wafers were mesa etched, a dielectric film was deposited for step coverage. A plasma-enhanced chemical vapor deposition system was used. A low temperature process was adopted to avoid heating the devices. A silane/oxygen plasma at 200°C for 90 minutes was used for optimum step coverage. This low temperature silicon dioxide layer was amorphous with low dielectric strength. A dielectric covered sample is shown in Fig. 3.

The fourth step is opening contact holes. At this stage, wafers were covered by PECVD SiO_2 everywhere. The mesa mask was used to open a hole where previously ohmic metals were deposited. The image reversal process as described in the first step with a careful alignment was required. The silicon dioxide on the top of ohmic metals was RIE-etched using gaseous plasmas of CHF_3 and CF_4. It was difficult to tell, under the microscope, whether ohmic metal has been reached. By probing the adjacent diodes and measuring the electrical properties, we made certain the dielectric had been removed completely and could move to next step. Fig. 4 shows the diode at this stage.

The fifth step is front side protection. The wafer prior to substrate removal has to be protected and supported on its front side. Wafers after backside thinning were less than one μm thick and simply too fragile to work on. A remedy is to spin a thin photoresist on the front side and then plate thick metal for support. The thin PR and plated metal could be striped off in the last step.

The sixth step is backside thinning. Selective etching was used for the substrate removal. In the GaAs/AlGaAs system, $NH_4OH:H_2O_2$ (1:24) was used. Hydrogen peroxide helps oxidizing GaAs whose oxide can be removed by ammonium hydroxide. The selectivity is a function of the percentage of Al composition in AlGaAs, and has to be high enough to stop etching. The subtle change of sample color implied the remaining thickness of the GaAs substrate. After the stop layer was reached, the thin AlGaAs film was then removed by hydrofluoric acid which would not attack GaAs. In the InGaAs system, hydrochloric acid quickly removed the InP substrate but did not attack the InGaAs epi-layer. These thinned samples were ready for the final metallization.

The final step is the metallization and plating. Backside metallization was performed after substrate thinning. The same ohmic metals as for the front side contact were evaporated. If samples have been exposed in the air, the accumulated surface oxide should be removed before metallization. After metallization gold, for its good conductivity, was plated on the back for mechanical support. The process was done after we removed the front side protection by acetone. The samples were about 20 µm thick.

The finished device was a vertical diode with ohmic metal on the top and bottom. We have been successful in fabricating 1 µm, 2 µm, 4 µm and 10 µm diameter diodes. Fig. 5 shows the multijunction honeycomb structure for 4 µm diodes. All the diodes were evenly arranged in 125x125 µm squares, cut by diamond saws and bonded in a fixture. They are now ready for RF testing in a whisker mount.

III. Planar Doped Barrier Subharmonic Mixer Performance

The subharmonic mixer diodes were first characterized by their DC performance. Fig. 6 shows the I-V characteristics of a 4 µm diameter GaAs PDB diode of 0.7 volt barrier height. The low frequency capacitance was about 20 fF. The effective depletion length is approximately 700 Å. Fig. 7 shows the I-V curves for InGaAs 2 µm diameter devices with barrier heights of 0.3, 0.5 and 0.7 volts respectively. The capacitance of InGaAs 10 µm diodes was 170 fF, which scaled down to a value of 6.9 fF for 2 µm ones. The ideality factor was determined by the slope of I-V between 10 µA and 100 µA. The resulting value for PDB diodes with 0.7 volt barrier height was 2.34 for GaAs and 2.39 for InGaAs.

The RF measurement results for 4 µm GaAs diodes are shown in Table 1. The diode was tested as a subharmonic mixer with a pump frequency of 100.5 GHz, a signal frequency of 202 GHz and an IF frequency of 1 GHz. The mixer was a whisker-contact diode mount which was designed to match a device of 5 fF capacitance at about 200 GHz. The tested 4 μm diode capacitance was 20 fF. With a pump power of 8 milliwatts, the mixer conversion loss was 18 dB. The mismatch was estimated at 7 dB, which implied a diode conversion loss of 11 dB. Measurements on the smaller devices and InGaAs devices are in progress.

V. Conclusion

The properties and fabrication techniques for planar doped barrier subharmonic mixer diodes have been described. The fabrication process produces mesa diodes for whisker contact mounts with diameters between one and ten microns. The diodes are based on the GaAs or InGaAs system and have barrier heights of 0.3, 0.5 and 0.7 volts. Initial subharmonic mixer results for a 4 μm diameter GaAs diode with 0.7 volt barrier height gave a conversion loss of 18 dB at 202 GHz with a local oscillator power of 8 milliwatts and an expected mismatch loss of 7 dB.

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Device profile of GaAs subharmonic PDB diodes

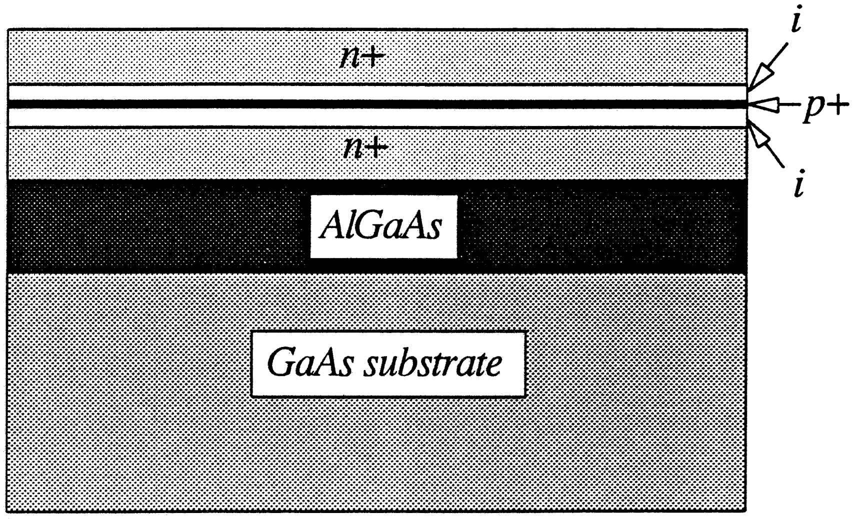
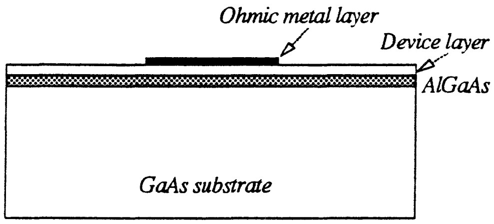
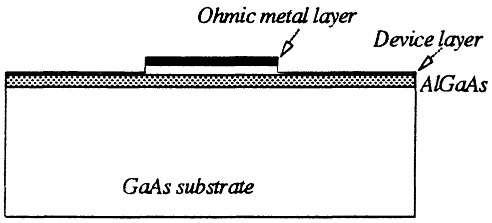


Figure (1) The device profile of GaAs subharmonic PDB diodes. The width of the intrinsic layer is 250 Å and that of the n^+ is 2500 Å on either side of the p^+ spike. The sheet charge doping density of the p^+ spike is 1.5, 2.0 and 2.5×10^{12} cm^{-2} for 0.3, 0.5 and 0.7 volt barrier height respectively.

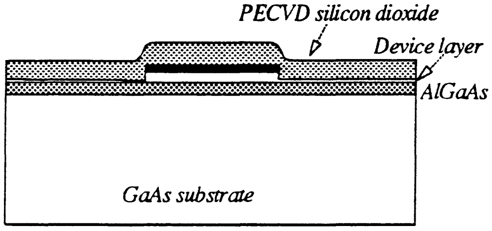
(1) Diode definition and metallization



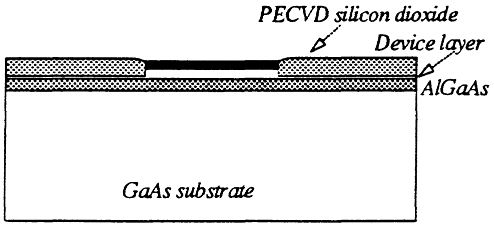
(2) Mesa etch



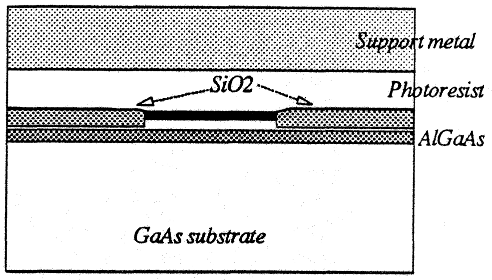
(3) SiO2 Passivation



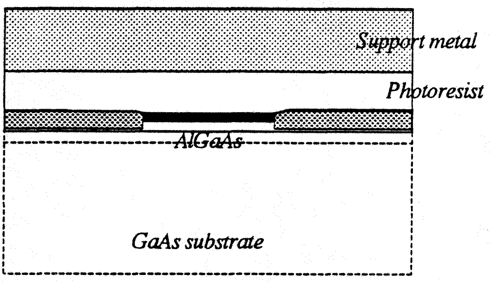
(4) Opening contact holes



(5) Front side protection



(6) Backside thinning



(7) Final metallization and plating

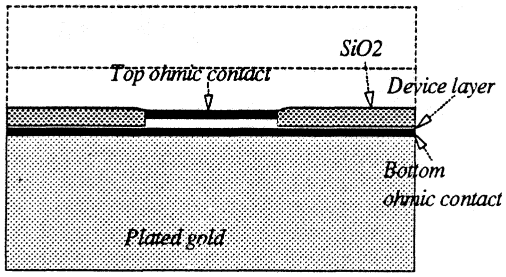


Figure (2) The fabrication sequence for GaAs subharmonic mixer diodes.

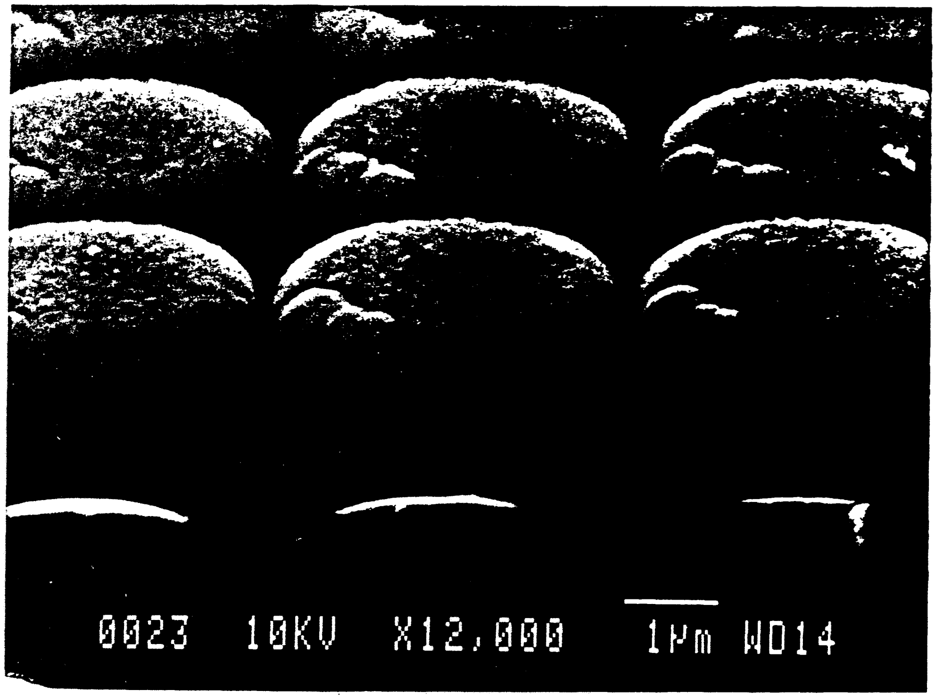


Figure (3) Diodes are covered by PECVD silicon dioxide everywhere. This picture was taken after fabrication step (3) as described in figure (2).

Figure (4) Contact holes are opened on the ohmic metals. This picture was taken after fabrication step (4) as described in figure (2).

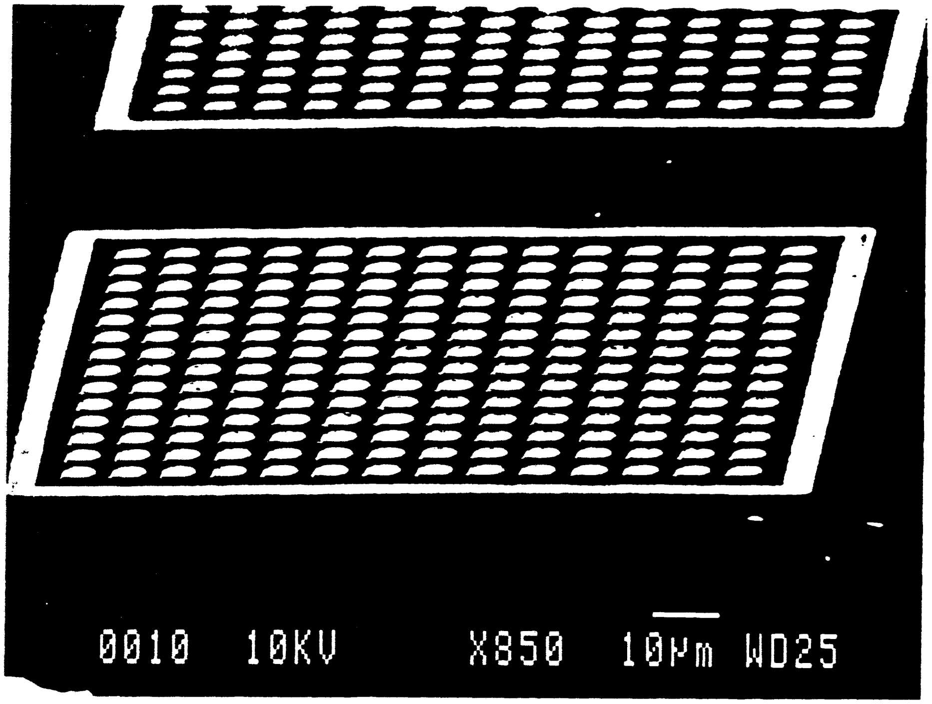


Figure (5) Finished diodes of honeycomb structure are in 125x125 µm squares. The dark area is covered by the dielectric layer.

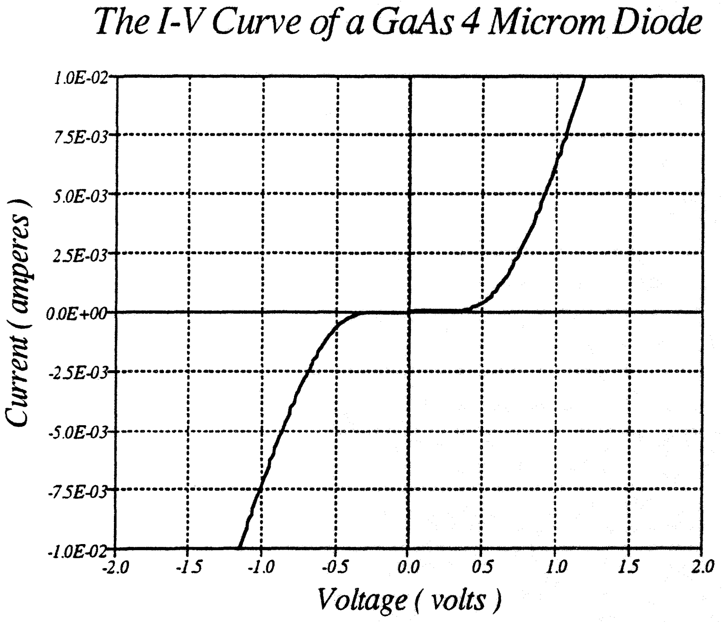


Figure (6) The I-V curve of a 4 μm GaAs subharmonic PDB diode.

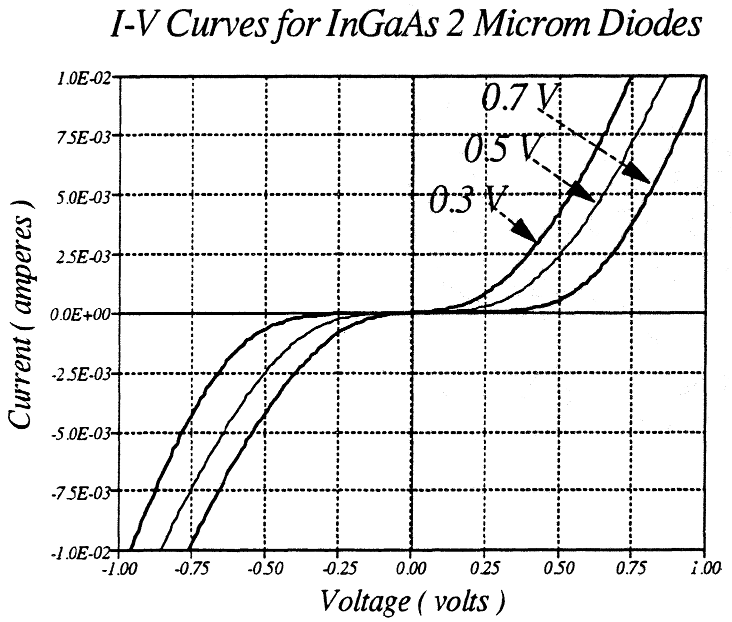


Figure (7) The I-V curves for 2 μm InGaAs diodes of 0.3, 0.5 and 0.7 volt barrier height, respectively.

Mixer Diode Performance (GaAs)	
Diode diameter	4 μm
p^+ spike doping	2.5×10^{12} cm^{-2}
Total *i* layer length	525 Å
Estimated barrier height	0.7 V
Ideality factor	2.39
Diode capacitance (measured)	20 fF
Contact resistance (by $\rho = 5 \times 10^{-7}$ Ω-cm^{-2})	3.9 Ω
RF	202 GHz
IF	1.0 GHz
LO	100.5 GHz, 8 mW
Mixer conversion loss	18 dB
Mixer waveguide impedence	150 Ω
Series inductance	0.01 nH
Mismatch loss	7 dB
Diode conversion loss	11 dB

Table (1) The performance of a 4 μm GaAs PDB diode as a subharmonic mixer.