Subharmonic Planar Doped Barrier Mixer Conversion Loss Characteristics

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Abstract —Planar doped barrier (PDB) diodes have been successfully used in a subharmonically pumped coplanar-stripline mixer circuit. A comparison is made in the conversion loss of the symmetric and asymmetric PDB diodes. A dramatic decrease in conversion loss is obtained when the PDB diode $I-V$ curve is perfectly symmetric. A minimum conversion loss in the order of 5.0 dB is obtained at a signal frequency of 2.0 GHz.

I. INTRODUCTION

$\mathbf{S}$CHNEIDER AND SNELL [1] reported on the first subharmonically pumped mixer using an antiparallel conducting pair of Schottky-barrier diodes. However, the performance of subharmonic mixers which utilize a pair of Schottky-barrier diodes is critically dependent upon matching the electrical characteristics of the two diodes as well as their placement in the microwave circuit. In the case of Schottky-barrier diodes, it is impossible to exactly match the $I-V$ characteristics due to the sensitivity of surface preparations and contact metallization. A much more attractive alternative is to make a symmetric characteristic in a single diode. The planar doped barrier (PDB) diode has this characteristic, and by using molecular beam epitaxy (MBE) in the growth, the symmetry of the $I-V$ curve can be made absolutely perfect.

We have developed a novel subharmonic mixer circuit and compared the conversion-loss properties for PDB diodes with both symmetric and asymmetric $I-V$ characteristics. By evaluating both types of PDB structures, the experimental data dramatically demonstrates the merits of matching $I-V$ characteristics. In this work, we demonstrate how a slightly asymmetrical $I-V$ characteristic can lead to degraded performance of the mixer by increasing the conversion loss. Pairs of Schottky-barrier diodes normally exhibit asymmetry. In addition, the ability to design the barrier height and capacitance in the PDB diode makes them ideally suited for use in millimeter-wave subharmonic mixers.

II. PDB DIODE THEORY

The PDB concept has been described in previous publications [2], [3]. The PDB is a majority carrier device structure with an n^+-i-p^+-i-n^+ doping configuration in which an extremely thin, fully depleted acceptor layer (20–100 Å) is used to form a triangular potential profile of
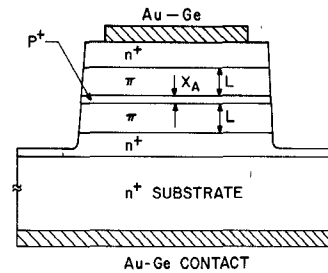
Fig. 1. Schematic cross section of a GaAs PDB diode with a symmetric current–voltage characteristic (not drawn to scale).

predetermined shape and height. For the particular case of a symmetric $I-V$ curve for a subharmonic mixer, the acceptor layer is positioned in the middle of the undoped region and separated by the distance L from each of the respective donor regions, as shown schematically in Fig. 1.

Assuming that the ionized impurity widths of the acceptor layer and at the edges of the donor layers are much less (typically < 100 Å) than the distance L, and the potential due to the ionized impurities in the undoped regions is negligible, then the zero-bias barrier height ϕ_{B0} is given approximately by

$$\phi_{B0} = \frac{qN_A X_A L}{2\epsilon} \tag{1}$$

where q is the unit electron charge, N_A the volume acceptor density, X_A the acceptor width, and ϵ is the dielectric permittivity of the semiconductor.

The capacitance of the diode which is constant with applied voltage is approximately equal to

$$C = \frac{\epsilon a}{2L} \tag{2}$$

where a is the diode area.

The symmetric $I-V$ characteristic of the diode can be expressed by a hyperbolic sine function [3] of the applied voltage V, whereby

$$I = 2I_s \sinh\left(\frac{qV}{nkT}\right). \tag{3}$$

The saturation current I_s is related to the zero-bias barrier height by

$$I_s = aA^* T^2 \exp\left(\frac{-q\phi_{B0}}{KT}\right). \tag{4}$$

In (3) and (4), k is Boltzmann's constant, T the absolute temperature, and A^* the effective Richardson constant.

The n-factor in (3) is determined by the geometry of the diode which effectively divides the applied voltage across the barrier region. Ideally, $n = 2$ for a truly symmetric PDB diode. The n-factor should not be confused with the so-called ideality factor which is an empirical parameter used to describe the effects of image force lowering and interface traps in Schottky barriers.

Schneider [4] has reported on the electrical properties of diodes exhibiting symmetric $I-V$ characteristics for frequency conversion. An ac analysis was performed through a Taylor series expansion of the nonlinear current waveform. The key features derived from this analysis are: a) there is no dc current flowing through the junction; b) the device current contains only odd-order harmonics of the pump frequency; and c) the conductance contains only even-order harmonics of the pump frequency.

The conversion loss L of the mixer operated at a pump frequency $2W_p$ is now given by [1]

$$L = \phi\left(Y_{\text{image}}, y_1/y_0, y_2/y_0\right) \tag{5}$$

where ϕ is an irrational function of the image conductance Y_{image} and the first two normalized Fourier coefficients of the conductance waveform. The properties of the function ϕ are extensively treated in the work by Salek [5]. For the special case $\alpha V_p \gg 1$ and for $Y_{\text{image}} = 0$, Y_{signal}, or ∞, the resulting conversion loss is

$$L\left(Y_{\text{image}} = 0\right) = 1 + \left(2/\alpha V_p\right)^{1/2} \tag{6}$$

$$L\left(Y_{\text{image}} = Y_{\text{signal}}\right) = 2\left(1 + \sqrt{2}/\alpha V_p\right) \tag{7}$$

$$L\left(Y_{\text{imag}} = \infty\right) = 1 + 2/\left(\alpha V_p\right)^{1/2}. \tag{8}$$

This means that the minimum conversion loss which can be achieved with an open or short at the image frequency is 0 dB. The minimum conversion loss for a matched image is 3 dB. The minimum conversion loss for a series resistance $R_s \neq 0$ is a function of W_s/W_c where W_s is the signal frequency and W_c is the diode cutoff frequency. In this investigation, the minimum conversion loss obtained was in the order of 5 dB.

III. DIODE FABRICATION AND DC CHARACTERISTICS

GaAs PDB structures were grown by MBE in a Varian-360 system. Silicon and beryllium were used as n-type and p-type dopants, respectively, at levels of approximately 10^{18} cm^{-3}. The undoped regions were low 10^{14} cm^{-3} p-type, thus contributing negligible charge to the potential. Typical growth parameters were as follows: growth rate $r = 200$ Å/min; substrate temperature $T_s = 580°$C; and flux ratio As$_4$/Ga $= 2$. Mesa diodes were formed by chemical etching and alloying of evaporated Au/Ge contacts to result in the structure shown in Fig. 1.

The parameters for the symmetric PDB diode are the following: planar acceptor density $N_A X_A = 3.6 \times 10^{11}$ cm^{-2}, undoped region widths $L = 2000$ Å, and mesa diameter of 100 μm ($a = 7.85 \times 10^{-5}$ cm^2). The dc $I-V$ curve for this diode is shown in Fig. 2. The excellent symmetry for the $I-V$ curve was checked with a dc electrometer. Within
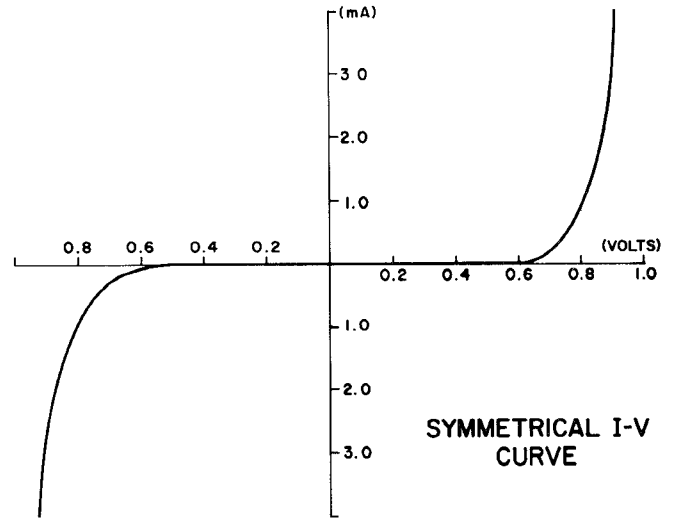

Fig. 2. Current–voltage characteristic of the symmetric PDB diode with the following diode parameters: $N_A X_A = 3.6 \times 10^{11}$ cm^{-2}, $L = 2000$ Å, area $= 7.85 \times 10^{-5}$ cm^2.
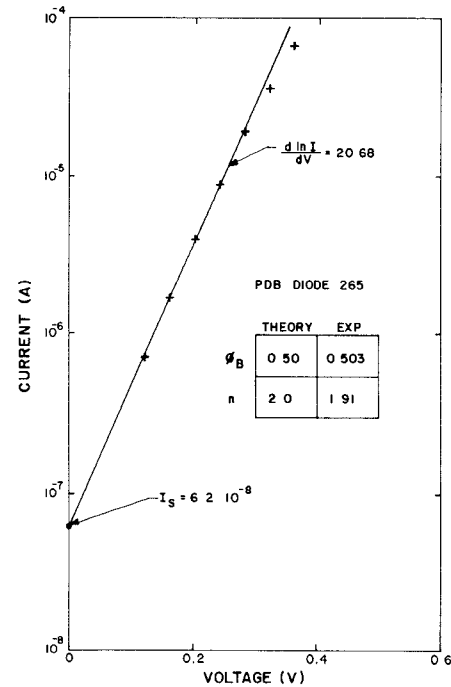

Fig. 3. Log current–voltage characteristic of PDB diode 265. The slope and intercept are used in determining the diode n-factor and barrier height, respectively.

experimental error, there was no measurable difference between the forward and reverse $I-V$ characteristics. A logarithmic plot for the current dependence upon applied voltage for the symmetric PDB diode is shown in Fig. 3. The equations for determining the n-factor and zero-bias barrier height ϕ_{B0} are found by taking the natural log of (3) and (4)

$$\frac{d(\ln I)}{dV} = \frac{q}{nkT} \tag{5}$$

$$\phi_{B0} = \frac{-kT}{q}\ln\left(\frac{I_s}{aA^*T^2}\right). \tag{6}$$

Thus, n and ϕ_{B0} can be determined from the slope and intercept of the log $I-V$ curve. From the inset box in Fig.
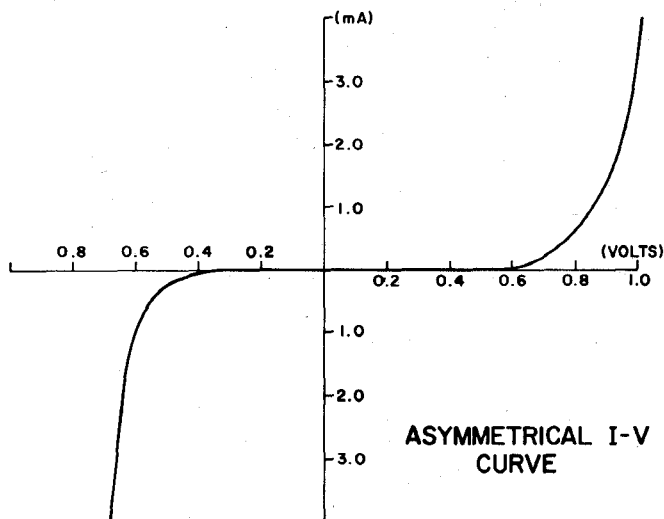
Fig. 4. Current–voltage characteristics of the asymmetric PDB diode.

3, there is seen to be excellent agreement between the theoretical and experimental calculations of these parameters. These results demonstrate that MBE provides the requisite control necessary to form PDB device structures. Fig. 4 shows the asymmetrical $I-V$ curve of a 100-μm PDB diode used in this investigation to make a comparison with the symmetrical case. The difference in the forward and reverse turn-on voltage is approximately 0.2 V.

IV. SUBHARMONIC MIXER RESULTS

The symmetric PDB diodes were evaluated in a subharmonic mixer using a coplanar waveguide fixture fabricated on a 1-in × 1-in × 0.015-in Al_2O_3 substrate. The ground planes and center conductor were formed by photolithography and AU evaporation. The diode wafer was sliced into 0.080-in-square chips and one diode on a chip was wire-bonded to the coplanar waveguide. A photograph of the resultant test fixture for the subharmonic mixer is seen in Fig. 5.

A series resistance of $R_s = 7\ \Omega$ and capacitance of $C = 1.8$ pF was measured for the symmetric PDB diode. This corresponds to a cutoff frequency of $f_c = 12.6$ GHz which, therefore, restricted RF measurements to a few gigahertz. Using separate signal generators as the local oscillator and signal source, the conversion loss was measured as a function of the symmetry of the $I-V$ characteristic. Fig. 6 shows the dependence of the conversion loss on intermediate frequency (IF) for a PDB diode with both asymmetric and symmetric $I-V$ curves. The conversion loss for the asymmetric case varies from 8 to 14 dB as the IF frequency varies from 400 MHz to 2 GHz. Over this same range of frequencies for the symmetric $I-V$ case, the conversion loss varies from 5 to 8 dB. This data shows the rather large decrease in conversion loss when the PDB diode has a perfectly symmetric $I-V$ characteristic. It should be noted that this mixer action was achieved at a pump power in the order of 9 dBm for the LO, which is somewhat lower than the required pump power for GaAs Schottky-barrier diode mixers. This demonstrates that a substantial reduction in the LO power can be achieved
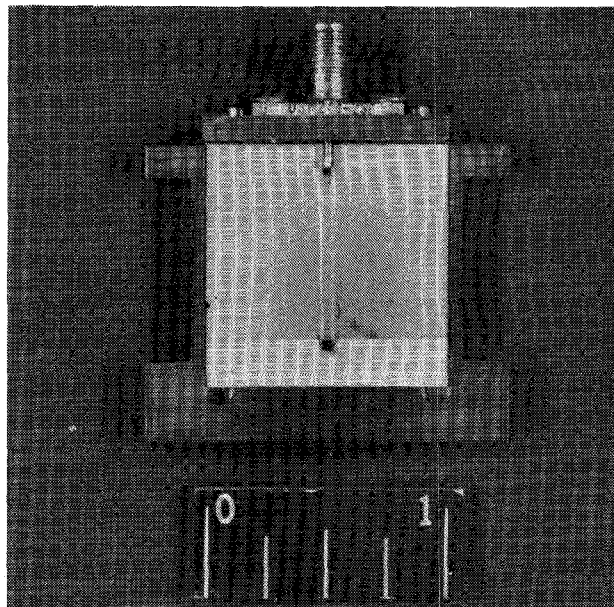

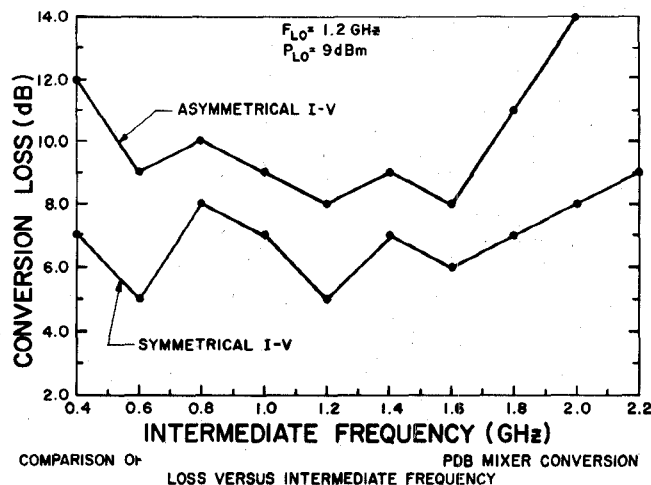Fig. 5. Photograph of subharmonic PDB diode test fixture.

Fig. 6. Comparison of symmetrical and asymmetrical PDB mixer conversion-loss versus intermediate frequency.

with the designable barrier height in the PDB diode. The symmetric PDB diode had a barrier height of 0.5 V, so that further decrease in the barrier height should lead to an even lower required pump power for the mixer. Pumping of the PDB mixer has also been achieved at submultiples of less than one half the signal frequency without significant degradation of the conversion loss. This possibility is attractive for use in the very high millimeter-wave frequency range.

These preliminary results clearly demonstrate the potential use of the PDB diode in subharmonic and conventional mixer circuits. Work is presently under way in the development of PDB diodes for microwave and millimeter-wave mixers.

V. CONCLUSION

A novel subharmonic mixer has been demonstrated which uses PDB diodes with both symmetric and asymmetric $I-V$ characteristics. The data shows a dramatic decrease in

the conversion loss when a perfectly symmetrical PDB diode is evaluated. This decrease is shown to be in the order of 5 dB. In this subharmonic mixer configuration, a single PDB diode replaces two well-matched Schottky-barrier diodes in conventional balanced mixers, and the designable barrier height reduces the local oscillator power. These results are presently being applied in the design of very high frequency millimeter-wave subharmonic mixers.

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REFERENCES

[1] M. V. Schneider and W. W. Snell, Jr., "Harmonically pumped stripline down-converter," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 271, 1975.
[2] R. J. Malik, R. T. AuCoin, R. L. Ross, K. Board, C. E. C. Wood, and L. F. Eastman, "Planar doped barriers in GaAs by molecular beam epitaxy," *Electron. Lett.*, vol. 16, p. 836, 1980.
[3] R. J. Malik, K. Board, L. F. Eastman, C. E. C. Wood, T. R. AuCoin, and R. L. Ross, "Rectifying variable planar-doped-barrier structures in GaAs," in *Inst. Phys. Conf. Ser.*, vol. 45, 1981, p. 697.
[4] M. V. Schneider, "Electrical characteristics of metal-semiconductor junctions," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, p. 1169, 1980.
[5] A. A. M. Saleh, *Theory of Resistive Mixers*, (*Res. Monograph 64*). Cambridge MA: M.I.T. Press, 1971.

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Samuel Dixon, Jr. (SM'74) received the B.S. degree in physics from West Virginia State College, Institute, WV, and the M.S. degree in electronic engineering from Monmouth College, West Long Branch, NJ, in 1972.

After serving three years in the U.S. Army Field Artillery as a First Lieutenant, he joined the U.S. Army Signal School as a Radar Instructor. He transferred to the U.S. Army Electronics Laboratories in 1958. Since that time he has been involved in research and development programs involving solid-state ferrite and semiconductor components for microwave and millimeter-wave radar, communications, and electronic-warfare systems. He is presently with the Electronic Technology and Devices Laboratory of the Electronic Research and Development Command, Fort Monmouth, NJ.

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Roger J. Malik (M'76) was born in New York City on August 3, 1954. He received a B.E. degree, with high honors, in electrical engineering from the State University of New York at Stony Brook in 1976, and the M.S. and Ph.D. degrees in electrical engineering from Cornell University in 1978 and 1981, respectively.

From 1978 to 1982 he held the position of Research Physical Scientist in the Electronic Materials Research Division, U.S. Army Electronics Technology and Devices Laboratory, Fort Monmouth, NJ. His principal areas of expertise are in advanced semiconductor device structures formed by molecular beam epitaxy (MBE). While at Fort Monmouth, he invented the planar doped barrier (PDB) concept, which was also the subject of his Ph.D. thesis. The PDB technique allows, for the first time, designable control over key electronic device parameters, including the potential barrier height, degree of rectification, and capacitance, which contrasts with the nearly fixed electrical properties exhibited by Schottky barriers. In November 1982, he joined Bell Laboratories to pursue research on high-speed PDB devices, including mixer diodes, photodetectors, switches, and hot-electron transistors.

Dr. Malik has received several awards for his work on planar doped barrier devices, which include the U.S. Army Special Act Award and the Paul A. Siple Award at the 1982 Army Science Conference. He has published or presented over thirty technical papers and has several patents pending. He is a member of APS and Tau Beta Pi.

Diode Detector Characteristics for a 94-GHz Six-Port Application

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Abstract — The suitability of commercially available diodes as power detectors in a 94-GHz six-port is examined. Square law response, noise, variation of reflection coefficient with power, and temperature effects are studied. The results show that silicon Schottky diodes are the best available.

I. INTRODUCTION

ALONG WITH THE renewed interest in 94-GHz radar systems, there is a need for fast and accurate testing at these frequencies. One very promising approach is the six-port automatic network analyzer which has undergone considerable development at microwave frequen-