VARACTOR DIODES FOR MILLIMETER AND SUBMILLIMETER WAVELENGTHS

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ABSTRACT

Whisker-contacted GaAs Schottky barrier varactor diodes are the most common high-frequency multiplier element in use today. They are inherently simple devices that have very high frequency response and have been used to supply local oscillator power for Schottky heterodyne receivers to frequencies approaching 700 GHz. This paper discusses the development of improved varactor diode technology for space based applications at millimeter and submillimeter wavelengths.

I. INTRODUCTION

Whisker contacted GaAs Schottky varactor diodes are presently in use to supply local oscillator power at frequencies as high as 700 GHz for ground based and airborne applications [1,2,3]. These diodes are also used in the Microwave Limb Sounder on NASA's Upper Atmosphere Research Satellite which is now monitoring global ozone depletion [4]. Although these devices have proven to be quite useful, there is great interest in developing technologies that are more mechanically robust, have higher operating frequency and have the potential to generate greater amounts of power. This paper will review recent work at the University of Virginia on multiplier elements. This includes both the development of planar Schottky varactors and investigation of new devices that have the potential for improved performance.

Section II will review our first attempt to fabricate a planar varactor diode for use at millimeter wavelengths. The preliminary design is presented and the limitations of this structure are considered. A next generation device is then proposed. It is hoped that this new device will become a standard replacement for a very successful and commonly used whisker-contacted varactor diode (U.Va.-6P4). Through development of this device we hope to demonstrate the potential of planar varactor technology and investigate the factors that will most seriously degrade planar varactor performance at high frequency.

We are developing varactor diodes for a multiplier chain to 1 THz. This system will incorporate two doublers (80 to 160 GHz and 160 to 320 GHz) and a tripler (320-960 GHz). The doublers will use multiple diodes integrated on a single chip to enhance power handling ability. These chips are designed to be used in a balanced doubler developed by Erickson [5]. The prototype doubler design and some preliminary results are presented in section III.

The tripler to 1 THz will be extremely challenging. Fortunately there is a great deal of effort being expended world-wide on new varactor structures which may be useful for this work. In section IV we will consider a variety of possible technologies, with special emphasis on an integrated δ–doped varactor diode pair and consideration of the new heterojunction barrier varactors. Section V is a brief summary of this work.

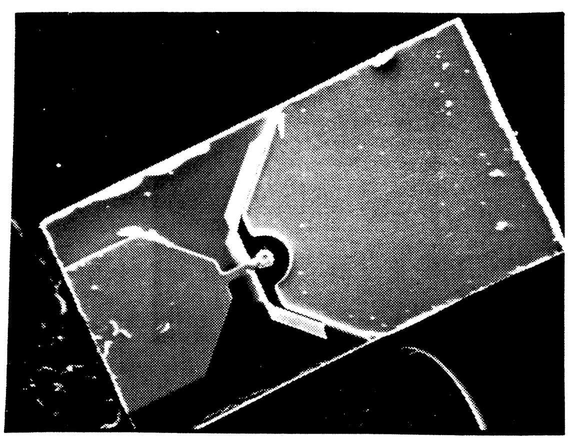
II. DEVELOPMENT OF A PLANAR VARACTOR TECHNOLOGY

As a first step in the development of planar varactor diodes we will fabricate planar devices to replace two commonly used whiskered diodes. These are the 6P4 diode, which is commonly used for doubling in the millimeter wavelength range, and the 2T2, which is used to double and triple at submillimeter wavelengths. The parameters of both of these devices are listed in Table I. The primary electrical benefits of the whiskered diode technology is the low shunt capacitance of the whisker and the ability of the diode user to tune the whisker inductance to optimize performance.

A scanning electron micrograph of a prototype planar varactor is shown in Fig. 1a. The surface channel fabrication procedure has been described previously [6,7]. The nominal parameters for this diode, designated SC6T1, are also listed in Table I. This diode was designed as a replacement for the 6P4 diode, however, there are two problems. First, series resistance is substantially higher than the 6P4's and second, the planar diode has a parasitic shunt capacitance of 12 fF which is unacceptably high. As might be expected, preliminary RF measurements have been disappointing. The excess series resistance is due to the use of

Table I: Schottky Varactor Diodes

Batch	Type	Anode Diameter (μm)	Epitaxial Layer Thickness (μm)	Epitaxial Layer Doping (cm^{-3})	Series Resistance (Ω)	Zero-bias Junction Capacitance (fF)	Minimum Junction Capacitance (fF)	Breakdown Voltage (V)
6P4	Whiskered	6	1.0	$3x10^{16}$	9.5	20	5.5	20
2T2	Whiskered	2.5	0.59	$1x10^{17}$	12	5.5	1.5-2.0	11
SC6T1	Planar	6.2	1.3	$2x10^{16}$	20	20	4	30



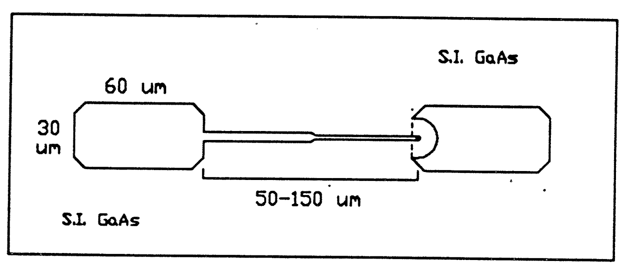


Fig. 1. a) A prototype planar varactor diode. The surface channel technology is used to achieve isolation between the contact pads [6,7]. b) A sketch of the second generation device which has smaller contact pads and variable finger length.

an epitaxial layer that is too thick and too lightly doped. Although this epitaxial layer yields a higher breakdown voltage, the penalty in R_s outweighs this benefit. Since the fabrication of the SC6T1, new material has been obtained and diodes with characteristics closer to those of the 6P4 will be fabricated.

The increased shunt capacitance of the planar diode is a serious problem. This capacitance is due primarily to the fringing field between the contact pads through the high dielectric constant GaAs substrate. To reduce this capacitance there are three options:

1) Reduce the pad dimensions,

2) Increase the pad separation (and therefore the finger length), and/or

3) Use a substrate with a lower dielectric constant.

The first two improvements will be implemented in our next generation device, as shown in Fig. 1b. The primary limitations on pad dimensions are the ohmic contact resistance and the need to make a reliable solder contact. Although the proposed pad width of 30 µm is about the minimum size that most users feel comfortable soldering to, it is clear that if smaller pads will lead to better performance, users will develop more elaborate soldering techniques. However, the minimum pad size is also limited by our ohmic contacts. We use SnNi/Ni/Au plating for our standard ohmic contact and reliably obtain resistivities of $10^{-5}\ \Omega cm^2$ or slightly less. Thus, a 30 µm x 30µm pad should have roughly one ohm of contact resistance. Smaller pads will require a significantly improved ohmic contact technology.

The new mask set will have several finger lengths, from 50 - 150 µm. This will allow evaluation of RF performance as a function of pad-to-pad capacitance and finger inductance. It is expected that one specific finger length will give optimum performance in a given multiplier mount at a given frequency. Thus, we expect that detailed RF evaluation of these devices will yield important guidelines for future chip designs.

The use of a quartz substrate for planar Schottky diodes has been demonstrated for mixer applications [7]. This has led to significant reductions in shunt capacitance which may be important for multiplier applications. However, the thermal properties of the GaAs Schottky diode on quartz are not well understood, and we have noticed that mixer diodes on quartz substrates are more likely to show signs of heating effects than equivalent diodes on GaAs. Since the removal of heat from the varactor diode is particularly important, it is not clear if quartz substrates will yield an overall performance benefit. Our next batches of planar varactors will have GaAs substrates. However, we also hope to investigate quartz and perhaps sapphire substrates in the near future.

III. INTEGRATED SCHOTTKY VARACTORS FOR BALANCED DOUBLING

The first step in the proposed multiplier chain to 1 THz is a doubler from 80 to 160 GHz. Since there are sources available that can deliver large amounts of power at 80 GHz, our goal is to develop a doubler that is fairly efficient, but, more importantly, can handle large input powers. With this goal in mind, a planar chip was designed based on the balanced doubler configuration of Erickson, which has generated up to 25mW at 160 GHz using two whisker contacted diodes [5].

One benefit of the planar diode technology is the ability to integrate several diodes on a chip to increase power handling ability. For example, when two diodes are placed in series their individual areas can be doubled in order to maintain the same total series resistance and junction capacitance as a single device. However, the series pair will have twice as much reverse breakdown voltage. The increased area and breakdown voltage will yield improved power handling ability. Two scanning electron micrographs of our prototype are shown in Fig. 2. The chip consists of four varactor diodes, two for each leg of the balanced doubler.

The design parameters and dc characteristics of the prototype balanced doubler chips are shown in Table II. Our goal was to achieve a reverse breakdown voltage of 20V for each anode. Also, the anode diameters of 10 and 12 μm were chosen to achieve zero-bias junction capacitances of 40 and 60 fF per anode. As is seen in the table, the first batch had excessive series resistance and extra breakdown voltage. This is due to the low doping density and thickness of the epitaxial layer. For the second batch this problem was corrected at the cost of reduced breakdown voltage. However, this trade-off is expected to yield significantly improved RF performance.

The capacitance-voltage (C-V) curves for a single diode and a diode series pair are shown in Fig. 3, indicating the increased breakdown voltage of the diode pair.

Preliminary RF tests for the first prototype balanced doubler were performed by Dr. Erickson at the University of Massachusetts and the results are presented in Table II. These initial results are quite encouraging, but not yet competitive with the whiskered-diode

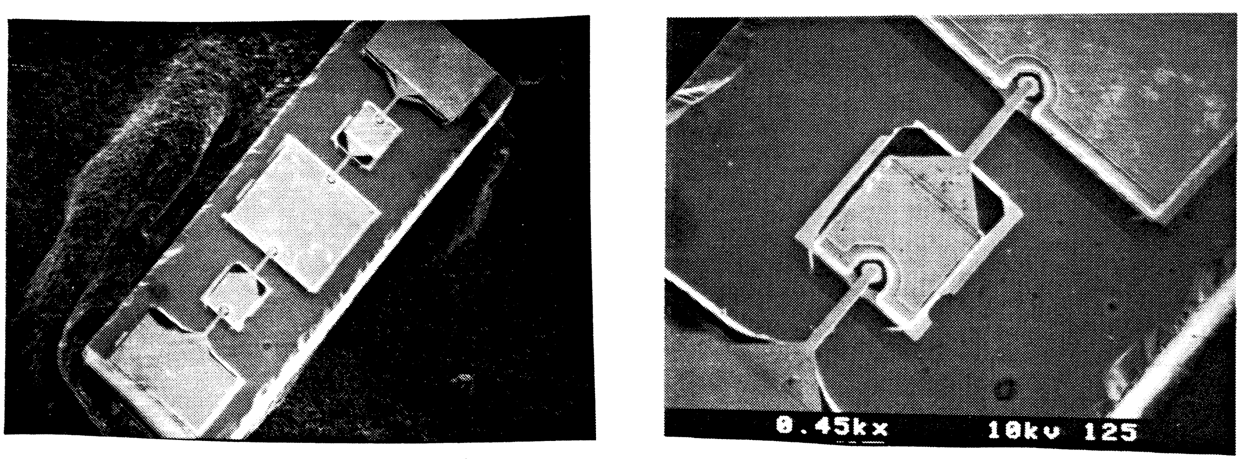


Fig. 2. SEM photographs of the prototype balanced doubler to 160 GHz.

Table II: Prototype Balanced Doubler Chips

DC Characteristics

Batch #	Epitaxial Layer Thickness (μm)	Epitaxial Layer Doping (cm^{-3})	Anode Diameter (μm)	Pair Series Resistance (Ω)	Pair Breakdown Voltage (V)
1	1.3	1.8×10^{16}	10	20	45
2	1.2	2.5×10^{16}	10	14	35

Preliminary RF Data†

Batch #	Input Freq. (GHz)	Output Freq. (GHz)	Input Power (mW)	Output Power (mW)	Efficiency (%)
1	82	164	55	3	6
1	82	164	100	6	6

† Preliminary RF data supplied by N. Erickson, University of Massachusetts. Measurements have not been performed with batch #2.

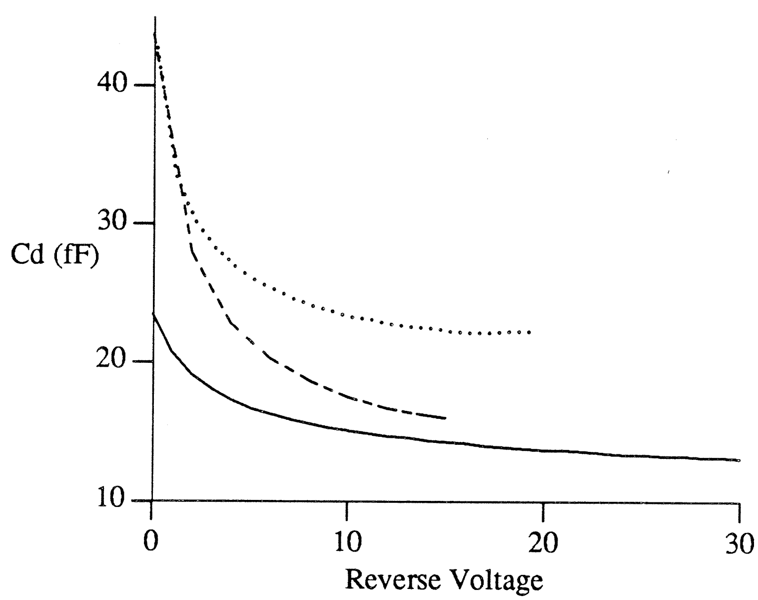


Fig. 3. C-V Characteristics of the prototype balanced doubler chip for a single varactor diode (dotted), a diode series pair (solid) and for a single diode with anode-to-pad connection to eliminate the pad-to-pad shunt capacitance (dashed).

results. Two changes in the chip design are planned to improve performance. The first is the increase in epitaxial layer doping to reduce series resistance, as was achieved with batch #2. The second is the reduction of pad-to-pad capacitance. The importance of this is demonstrated by the third curve (dashed) in Fig. 3. This curve was measured from the anode to ohmic contact pad on a diode that had no finger, and therefore does not include the pad-to-pad capacitance. This curve has much greater modulation and much lower minimum capacitance. This clearly demonstrates that the pad-to-pad capacitance is having a major effect on performance. The shunt capacitance of future chips will be reduced through a redesign of the contact pads and possibly through the use of quartz substrates.

Once the first stage multiplier has been optimized, the next step is to design a chip for the doubler to 320 GHz. Since the second stage will not have to handle as much power as the first, we will be able to trade-off some power handling ability in order to increase cut-off frequency. It is expected that the optimum diodes for this stage will have smaller anodes and higher epitaxial layer doping density.

There is much work to be done on the integrated balanced doublers. However, the prototype devices have yielded encouraging results, and the improvements necessary to increase performance are clearly defined. Thus, we expect to achieve significantly improved output powers at 160 GHz in the near future. Also, the lessons learned on the first stage doubler will be applied to the second stage, so that development of the higher frequency chips should progress more rapidly.

IV. POTENTIAL VARACTORS FOR TRIPLING TO 1 THZ

The development of a tripler to 1 THz is an extremely challenging task. Fortunately there are several device technologies that may yield suitable performance. We have chosen to investigate five of these, each of which is discussed in the following sections. The whiskered Schottky and planar Schottky are considered briefly and the new two-dimensional-electron-gas/Schottky (2-DEG/Schottky), which is considered in detail in a separate paper, is also only briefly overviewed. The other two technologies, the integrated δ–doped varactor pair and the heterojunction barrier varactor, are considered in more detail.

A. Whiskered Schottky Diodes

The most likely candidate for the first successful tripler to 1 THz is simply a standard whisker contacted Schottky varactor. The 2T2 diode has already been successfully used in triplers to 500-700 GHz and can probably be extended to the THz range. However, the efficiency will certainly be decreased and it is not clear how much output power will be achieved. A more optimized diode can probably be developed, perhaps with slightly higher doping density and smaller diameter. Although this technology appears to be reaching fundamental limitations [8], it should continue to be pursued because the probability of some level of success is high.

B. Planar Schottky Varactors

There are two advantages of using a planar Schottky device; the elimination of the fragile whisker contact and the opportunity to use several integrated diodes to increase power handling ability or achieve a more beneficial C-V characteristic. The drawback is the increased shunt capacitance that is inherent in the planar diode. There are several areas that must be researched. As discussed previously, these include the redesign of the contact pads and anode finger, and the use of low dielectric constant substrates. Also, the potential use of two Schottky varactors in an anti-series combination to achieve a symmetric C-V characteristic may have substantial benefits for tripling applications. It is not yet clear if planar Schottky technology will be useful at 1 THz, however we hope to answer many important questions through our development of planar diodes for lower frequencies.

C. The 2-DEG/Schottky Diode

This device consists of a metal contact to the edge of a two-dimensional-electron-gas (2-DEG) formed at a heterointerface. The capacitance is between the Schottky metal and the undepleted portion of the 2-DEG. The voltage on the Schottky metal modulates the depletion depth in the 2-DEG, thereby varying the capacitance. This device should benefit from increased electron mobility and perhaps higher electron saturation velocities compared to bulk devices. This may lead to significantly improved high frequency performance. Also, this is an inherently planar device. Prototype diodes have demonstrated excellent capacitance modulation and high reverse breakdown voltages. This new device is discussed in greater detail in a separate paper [9].

D. An Integrated δ-Doped Diode Pair

A design for a planar chip with two integrated δ-doped varactor diodes in a back-to-back configuration is shown in Fig. 4. The symmetric C-V characteristic of such a diode pair will yield significant benefits for tripler applications since an idler circuit at the second harmonic is not needed. The δ-doped diodes have been shown to have a sharp C-V characteristic [10,11]; which is a significant advantage at high frequencies since the available input power is quite low.

The planar tripler has been designed to produce a capacitance ratio (C_{max}/C_{min}) of 2.5, with an estimated cut-off frequency of 6 THz. The material structure is described in Table III. The mask set and epitaxial material for this device are now being purchased.

E. Evaluation of the Heterostructure Barrier Varactors

In 1990 Rydberg et al. demonstrated that a thin layer of high band-gap material sandwiched between two thicker layers of low band-gap material could yield a symmetric C-V characteristic that is ideal for tripler applications [12]. This Quantum (or Heterostructure) Barrier Varactor (QBV or HBV) has promise for high frequency multiplier applications, and is now being investigated by several groups. The goal of our investigation

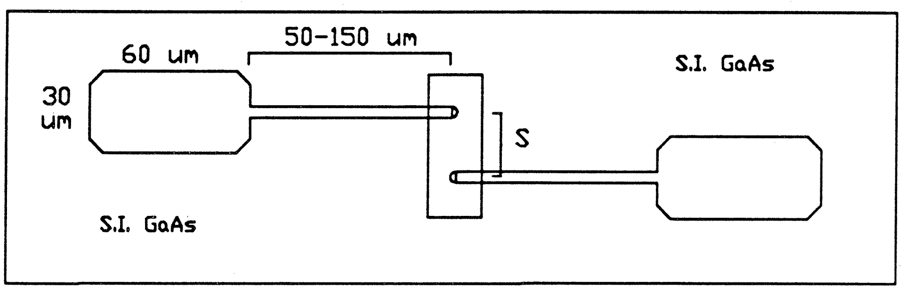


Fig. 4. A sketch of the proposed integrated δ-doped varactor pair. The finger length will be variable on the mask set and the anode spacing has not yet been determined

Table III: Epitaxial Material for the δ-doped Diode Pair

Layer Type	Doping Density	Thickness (μm)
N GaAs	$<1\text{x}10^{15}$ cm^{-3}	0.05
Si atomic layer	$3.4\text{x}10^{12}$ cm^{-2}	-
N GaAs	$2\text{x}10^{17}$ cm^{-3}	0.13
N^+ GaAs	$>3\text{x}10^{18}$ cm^{-3}	3.0
$Al_xGa_{1-x}As$ etch stop	undoped ($x \geq 0.5$)	2.0-2.5
GaAs substrate	S.I.	-

is to determine if HBVs offer significant improvement over standard Schottky technologies, and, if so, to demonstrate such improvement. To determine the potential of these devices we will discuss the design of HBVs that have characteristics similar to the state-of-the-art whiskered varactors whose characteristics were presented in Table I.

A schematic band diagram of a zero-biased single barrier GaAs/AlGaAs/GaAs HBV is shown in Fig. 5a. When a voltage is applied to the device a depletion region is created on one side of the barrier which increases in length as the voltage is increased. The capacitance of this device is approximated as

$$C = \frac{A}{X_B/\varepsilon_B + X_{D,total}/\varepsilon_M} \tag{1}$$

where A is the device area, ε is the permittivity of the barrier (B) and the modulation region (M) materials, X_B is the barrier layer thickness and $X_{D,total}$ is the total depletion layer thickness on both sides of the barrier as a function of voltage. The maximum capacitance can be as high as $\varepsilon_B A/X_B$ if there is negligible depletion in the modulation layers at zero-bias. The series resistance for a single barrier HBV, including spreading, epilayer and ohmic contact resistance, is estimated as

$$R_{1,s} = R_{1,spr} + R_{1,epi} + R_{1,oc} = \frac{1}{2d\sigma_S} + \frac{2X_M}{\sigma_E A} + \frac{R_c}{A} \tag{2}$$

where d is the anode diameter, σ is the conductivity of the substrate (S) and epilayer (E) materials, X_M is the length of the n-type modulation regions, and R_c is the specific resistivity of the ohmic contact. It is important to note that the device area affects not only the junction capacitance, but also the resistance of the ohmic contact. Therefore, although we can reduce the junction capacitance by shrinking the device area, this is not beneficial unless the ohmic contact resistivity, R_c, is low enough so that the third term in (2) remains negligible. For this study we will assume a specific contact resistivity of $10^{-7}\,\Omega\,\mathrm{cm}^2$, which is consistent with the best contacts reported in the literature.

An important parameter for all varactor diodes is the voltage at which the conduction current becomes significant. For a standard Schottky varactor, impact ionization in the depletion region determines the reverse breakdown voltage and thermionic emission over the Schottky barrier determines the forward conduction current. For the HBV either thermionic emission or avalanche breakdown can play the critical role, depending on the device parameters. Figure 5b shows an HBV band diagram with voltage applied, with a depletion region on one side of the barrier and an accumulation region on the other. As the HBV is biased, the accumulation region grows and therefore the effective barrier height, given by $\Delta E_c - qV_{acc}$, decreases. Simultaneously, the electric field strength in the depletion region grows. Whether avalanche breakdown or thermionic current occurs first depends primarily on the conduction band discontinuity ΔE_c and the band-gap in the modulation region.

We would like to have a method to compare HBV diodes to standard varactors. A simple computer model was developed in order to simulate the operation of the HBV under applied bias. The simulation assumes that little current flows through the device, and

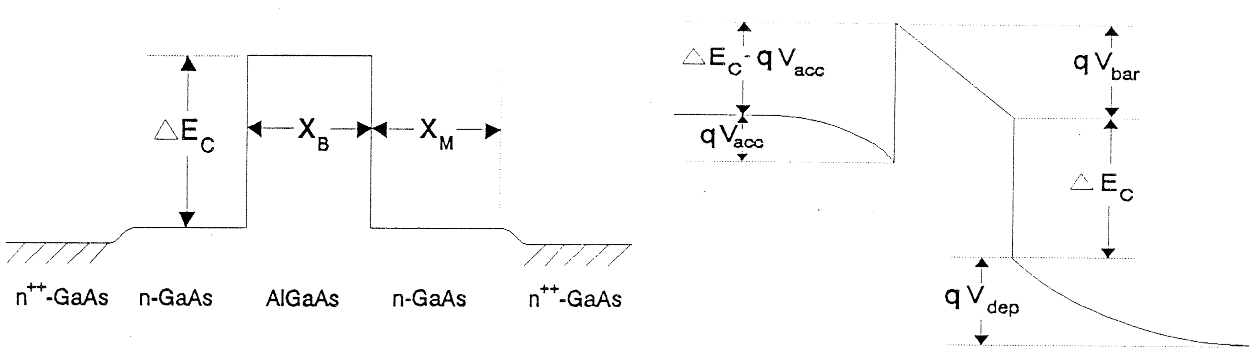


Fig. 5. The band-diagram of a simple Heterostructure Barrier Varactor (HBV), a) zero-bias and b) bias applied.

calculates the quasi-equilibrium band diagram for different bias levels. The approximations developed by Delagebeaudeuf et al. [13] are a relatively standard method to analyze a 2-DEG at a heterostructure interface. For our case, these approximations were extended to include additional energy levels due to the high doping density in the 2-DEG region. The most crucial parameter to estimate is the maximum voltage that can be applied before conduction current begins to degrade the multiplier efficiency. For this discussion we will assume that impact ionization becomes important at the voltage where the electric field strength exceeds a critical value. Since there is no experimental data from which to estimate the critical field of HBVs, we have assumed that the critical field will be similar to that of GaAs pn junctions [14]. For devices dominated by thermionic emission, the maximum voltage was assumed to be that voltage at which

$$\Delta E_c - qV_{acc} = nkT, \tag{3}$$

and we have assumed a value of n=5 for this study.

For GaAs/AlGaAs devices the value of ΔE_c is rather small ($\Delta E_c \approx 0.35$ [15]) and thermionic emission becomes important before impact ionization. Simulations show that for low doping levels (less than about 10^{16} cm^{-3}) these devices can have a maximum voltage comparable to a standard Schottky varactor, however, R_{epi} will be extremely large. Increasing the doping level decreases R_{epi}, but also decreases V_{max}, which indicates that single barrier GaAs/AlGaAs HBVs will have less power handling ability than standard Schottky varactors. There are several possible solutions to this problem, two of which will be considered in this paper; epitaxial stacking of barriers and the use of different material systems. Epitaxial stacking divides the applied voltage among several barriers, thus increasing the maximum device voltage. For an HBV with N barriers, $V_{N,max} = N \cdot V_{1,max}$.

As N is increased, it is best to increase the device area in order to maintain reasonable values of junction capacitance and modulation layer resistance. Assuming that the area is increased proportionally to the number of barriers, the series resistance of an N barrier HBV can be expressed as,

$$R_{N,s}=\frac{1}{\sqrt{N}}R_{1,spr}+\frac{N+1}{2N}R_{1,epi}+\frac{1}{N}R_{1,oc}. \tag{4}$$

This equation shows that the increase in area has the important effect of reducing the spreading and ohmic contact resistances. In fact, without using multiple barriers it would be impossible to fabricate an HBV with reasonable capacitance and series resistance unless the ohmic contact resistivity is exceptionally low.

Other material systems can have significantly higher values of ΔE_c. For example, the InGaAs/InAlAs system can yield barriers of near 0.8 eV, while the GaAs/GaN system allows 0.9 eV barriers. The computer simulation indicates that the maximum voltage in both of these material systems is limited by impact ionization, rather than thermionic emission.

In the following paragraphs, the simulation results for single and multiple barrier HBVs are discussed for the previously mentioned material systems. In order to compare the HBVs with the 2T2 and 6P4 varactors, barriers are added until V_{max} is greater than that of the standard varactor. The area is then chosen so that C_{min} of the HBV is the same as the standard varactor. A common varactor figure-of-merit used in our comparisons and listed in Table IV is the dynamic cut-off frequency, given by [16]

$$f_{co}=\frac{1/C_{min}-1/C_{max}}{2\pi R_s}, \tag{5}$$

where C_{max} and C_{min} are the maximum and minimum device capacitance.

GaAs/AlGaAs: Figure 6 shows the simulation results for GaAs/AlGaAs HBV's. As the modulation doping density is increased, more barriers are needed to achieve the desired maximum voltage and the series resistance is reduced due to the increase in both σ_E and device area. Table IV gives examples of GaAs/AlGaAs HBV's with V_{max}, C_{min} and R_s similar to the 2T2 and 6P4. However, the HBVs will have the added benefit of a symmetric C-V curve.

InGaAs/InAlAs: With the InGaAs matched to InP (i.e. 53% In), $In_{0.32}Al_{0.68}As$ will give a ΔE_c of about 0.8 eV with a 1% lattice mismatch. However, InGaAs has a narrower band gap than GaAs, and will thus have a smaller critical field for impact ionization. In these simulations, we used the critical field data versus doping for a Ge abrupt p-n junction [14] since Ge and $In_{0.53}Ga_{0.47}As$ have similar bandgaps. Because of the lower critical field, single barrier InGaAs/InAlAs HBV's will not have sufficient V_{max}, and thus multiple

Table IV: Heterostructure Barrier Varactors

Material System	N	X_B (μm)	N_{mod} (cm^{-3})	Diam. (μm)	V_{max} (V)	R_s (Ω)	C_{min} (fF)	C_{max} (fF)	f_{co} (THz)
GaAs/AlGaAs	1	0.02	$5x10^{16}$	2.3	4.0	37	1.5	22	2.6
	1	0.02	$1x10^{17}$	1.7	2.6	21	1.5	12	4.4
	1	0.02	$5x10^{17}$	1.0	1.2	19	1.5	4	3.4
(6P4-like)	5	0.02	$5x10^{16}$	9.0	20	7	4.5	66	4.6
(2T2-like)	5	0.02	$1x10^{17}$	3.8	13.2	11	1.5	12	8.6
InGaAs/InAlAs	1	0.02	$5x10^{16}$	2.6	6.7	25	1.5	32.3	4.0
	1	0.02	$1x10^{17}$	1.9	4.3	16	1.5	17.2	6.0
	1	0.02	$5x10^{17}$	1.2	2.8	16	1.5	6.4	5.1
(6P4-like)	3	0.02	$5x10^{16}$	8.0	20.0	5.5	4.5	97	6.0
(2T2-like)	3	0.02	$1x10^{17}$	3.4	12.9	9.5	1.5	17.2	10.4
GaAs/GaN	1	0.008	$5x10^{16}$	6.0	19.2	13	4.5	367	2.7
	1	0.008	$1x10^{17}$	2.5	11.4	20.5	1.5	63	5.1
(6P4-like)	2	0.008	$1x10^{17}$	6.1	23	5	4.5	190	7
(2T2-like)	2	0.008	$2.3x10^{17}$	2.8	18.2	9.5	1.5	38.6	10.7

barriers must be used. Figure 7 and Table IV show that devices similar to the 2T2 and 6P4 varactors can be achieved with three barriers.

GaAs/GaN: The GaAs/GaN material system has a high ΔE_c and the critical field of GaAs. The major disadvantage is that it is a relatively new material system on which little experimentation has been performed [17]. Our simulations showed that impact ionization will be the limiting factor for these devices. Single barrier GaAs/GaN HBV's have sufficient V_{max}, but tend to have higher R_s than comparable Schottky varactors due to modulation region resistance. Characteristics of single barrier GaAs/GaN HBV's are given in Table IV for several dopings. By using higher N_{mod} and multiple barriers, HBV's with low R_s and very little conduction current should be possible. Figure 8 and Table IV show that only two barriers are required to achieve device characteristics similar to the 2T2 and 6P4.

V. SUMMARY

Whisker-contacted GaAs Schottky barrier varactor diodes are the best multiplier elements available for millimeter and submillimeter wavelength applications. However, the development of planar diode technology and new devices promise to improve both system reliability and performance. Our prototype planar Schottky varactors are not yet competitive at millimeter wavelengths, but several straight-forward improvements in the chip design should alleviate the problems of high series resistance and shunt capacitance. The ability to integrate several varactor diodes onto a chip is being exploited to increase power handling ability, and an integrated balanced doubler for millimeter wavelengths has been described. The prototype devices have shown promising performance at 160 GHz and the second generation chips have greatly improved dc characteristics. Both the single-diode planar Schottky varactor and the balanced doubler will benefit from improved contact-pad/finger geometries and lower ohmic contact resistances. The use of low dielectric substrates is also being investigated.

Several device technologies may be useful for a proposed tripler to 1 THz. While the whisker-contacted Schottky diode is likely to be the first device to yield reasonable output power at this frequency, planar diodes and other device structures promise improved performance. The 2-DEG Schottky, δ-doped Schottky and the quantum (heterostructure) barrier varactors (QBV or HBV) are being investigated at U.Va. The 2-DEG Schottky research is described elsewhere [9]. An integrated δ-doped varactor pair with symmetric C-V was described and will be fabricated in the near future. The HBV devices are particularly promising. Our simple analysis has shown that HBVs with parameters similar to the state-of-the-art Schottky varactors can be designed if multiple barriers are used and ohmic contact resistances are in the $10^{-7}\,\Omega\,\mathrm{cm}^2$ range. These devices will also have the benefit of a symmetric C-V curve. The use of InGaAs/InAlAs or GaAs/GaN for the HBVs promises the best performance if epitaxial layers of the required quality can be obtained.

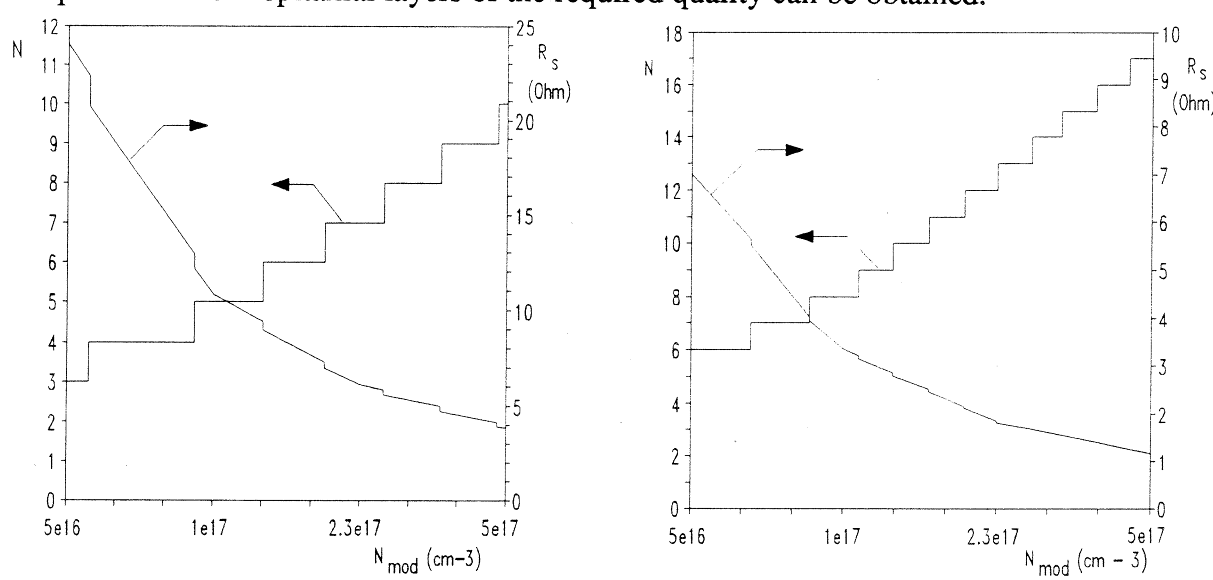


Fig. 6 The number of barriers necessary to achieve a GaAs/AlGaAs HBV with the same maximum voltage as the 2T2 (left) and 6P4 (right) varactors as a function of N_{mod}. *Also, shown is the series resistance when the area is chosen to yield the same minimum device capacitance as the standard varactors. Additional parameters are listed in Table IV.*

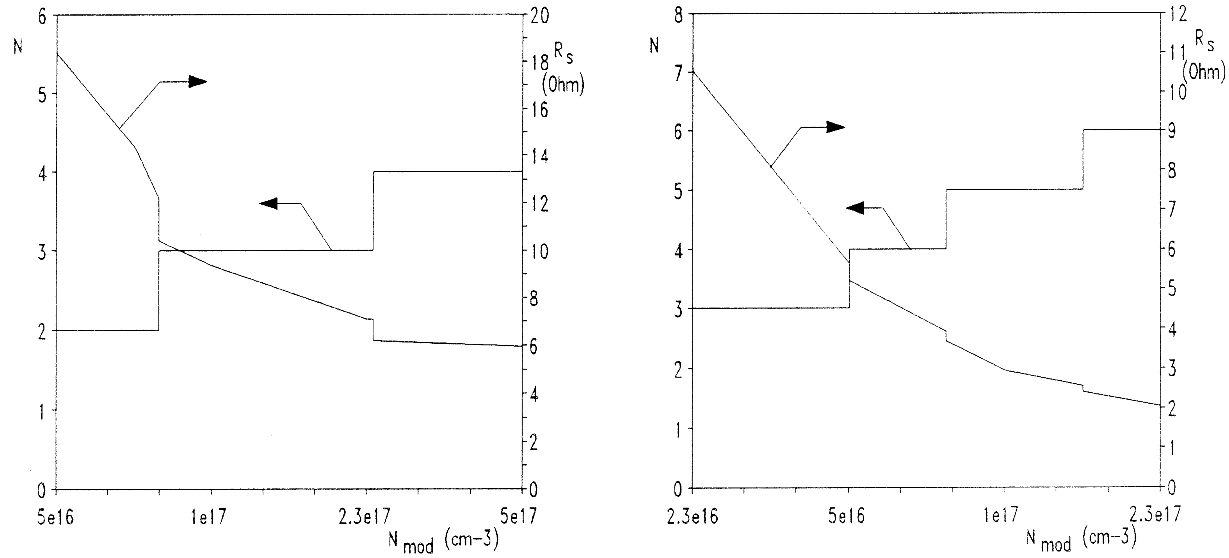


Fig. 7. The same as Fig. 6, but for InGaAs/InAlAs.

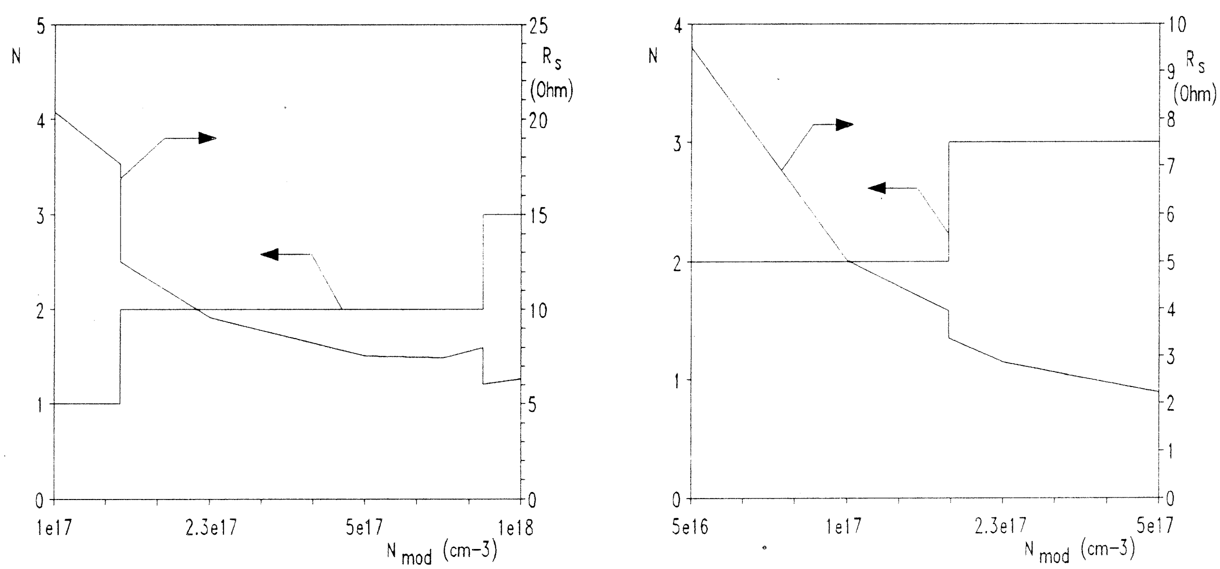


Fig. 8. The same as Fig. 6, but for GaAs/GaN.

ACKNOWLEDGEMENT

The authors would like to thank Dr. Neal Erickson (U. Mass, Amherst) for supplying the initial RF measurements on the prototype balanced doubler and Dr. Peter Siegel (Jet Propulsion Laboratory) for initial evaluation of the SC6T1 planar varactor. This work has been supported by the National Science Foundation under Grant ECS-8720850, NASA and the Jet Propulsion Laboratory.

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