Planar Varactor Diodes for Submillimeter Applications

Brian J. Rizzi, Kristan K. Rausch, Thomas W. Crowe, Philip J. Koh, William C.B. Peatman,
J. Robert Jones, Stephen H. Jones and Gregory Tait
Semiconductor Device Laboratory
Department of Electrical Engineering
Thornton Hall
University of Virginia
Charlottesville, VA 22903-2442

I. INTRODUCTION

Schottky barrier varactor diodes are used as frequency multipliers to supply local oscillator power for heterodyne receivers at millimeter and submillimeter wavelengths. Whisker contacted GaAs Schottky varactor diodes are the most common high-frequency multiplier element in use today. They have been used in heterodyne receivers to frequencies as high as 700 GHz for ground based, airborne and space applications [1,2,3,4,5]. Although the whisker contacted Schottky varactor diodes have proven very effective, there remains great interest in developing technologies which are more mechanically robust, have the potential to deliver larger amounts of power and are capable of operating well into the submillimeter wavelength range. This paper reviews the work at the University of Virginia on planar varactor technology for millimeter and submillimeter wavelength applications.

A multiplier chain to 1 THz using planar varactor diodes is being developed. The system consists of two doublers (80 to 160 GHz and 160 to 320 GHz) and a tripler (320 to 960 GHz). In Section II planar Schottky barrier varactor diode development is reviewed. An important goal is to demonstrate that planar diodes can replace whiskered devices without degrading performance. Preliminary results for a diode designed to replace the very successful U.Va.-6P4 whisker contacted diode are presented.

The doubler chips for the 1 THz multiplier chain incorporate multiple diodes for increased power handling ability, and are designed to be used in a balanced doubler circuit designed by Erickson [4]. The RF results for the 160 GHz doubler and the prototype design for the 320 GHz doubler are presented in Section III.

Developing a tripler to 1 THz is the most challenging part of the multiplier chain. The best devices today for this application are whiskered contacted Schottky diodes. To develop a planar tripler chip, we need to investigate novel varactor structures. A number of devices are being investigated as potential frequency doublers and triplers, and this work is presented in Section IV. An anti-series δ-doped varactor pair designed for tripling to 200-300 GHz is discussed first. This device technology is being evaluated as a potential tripler to 1 THz. A 2-DEG/Schottky varactor diode to be used as a frequency doubler has also been developed, and initial RF results are presented. Heterostructure barrier varactors are being investigated with emphasis on two material systems, GaAs/AlGaAs and GaAs/InGaAs/AlGaAs. Section V is a summary of the planar varactor diode work.

II. PLANAR SCHOTTKY BARRIER VARACTOR DIODE DEVELOPMENT

An initial goal in our development of planar Schottky barrier varactor diodes is to fabricate a planar device to replace the 6P4 diode, a very successful whiskered varactor diode used for doubling in the millimeter wavelength range. The parameters of this device are shown in Table I.

Prototype planar varactor diodes have been fabricated using the surface channel procedure [6,7,8]. A sketch of the surface channel structure is shown in Fig.1. The most challenging aspect of designing planar varactor diodes is reducing the shunt capacitance which is due mainly to the fringing field between the two contact pads. This added capacitance degrades the multiplier performance considerably. In addition, the anode contact finger length is fixed so device inductance cannot be tuned as it can be with a whiskered diode whose whisker length can be varied.

The first prototype planar varactor is designated SC6T1. Its parameters are also listed in Table I. Although this diode was designed as a replacement for the 6P4, its series resistance is substantially higher than the 6P4's, and the planar diode has a very large parasitic shunt capacitance of 12 fF. Preliminary RF measurements have been disappointing. A second generation device has been designed and fabricated with characteristics closer to those of the 6P4. An SEM photograph of the new device, designated SC6T2, is shown in Fig. 1, and the diode parameters are listed in Table I. The series resistance of the second batch of devices was decreased by reducing the epitaxial layer thickness and increasing the epitaxial doping density at the expense of a reduced breakdown voltage.

The shunt capacitance of the SC6T2 diodes was reduced to approximately 3-5 fF by shrinking the pad dimensions and increasing the pad separation. The pad size has been reduced to 30 μm x 60 μm, which is about the minimum size to which most users feel comfortable making a solder contact. Further reductions in pad size are also limited by the SnNi/Ni/Au ohmic contacts which have resistivities of $10^{-5}\Omega cm^2$ or slightly less. The SC6T2 diodes also have several finger lengths, ranging from 50 - 150 μm, which allows evaluation of RF performance as a function of pad-to-pad capacitance and finger inductance.

A tripler mount designed for whisker contacted diodes at the National Radio Astronomy Observatory has been obtained, and modified slightly to allow testing of planar diodes [9]. In Fig. 2 preliminary RF results for the SC6T2 planar varactors and 5M2 whiskered diodes (for which the mount was designed) are presented. It can be seen from the data that the efficiency of the SC6T2 diode increases as the 5M2 efficiency

Table I: Schottky Barrier Varactor Diodes

batch #	type	t_{epi} (μm)	N_{epi} (cm^{-3})	diam (μm)	C_{j0} (fF)	C_{shunt} (fF)	R_s (Ω)	V_{bkdn} (V)
6P4	whiskered	1.0	$3x10^{16}$	6.0	20	-	9.5	20
SC6T1	planar	1.3	$2x10^{16}$	6.2	20	12	20	30
SC6T2	planar	0.86	$4x10^{16}$	6.0	25	3-7	6	15

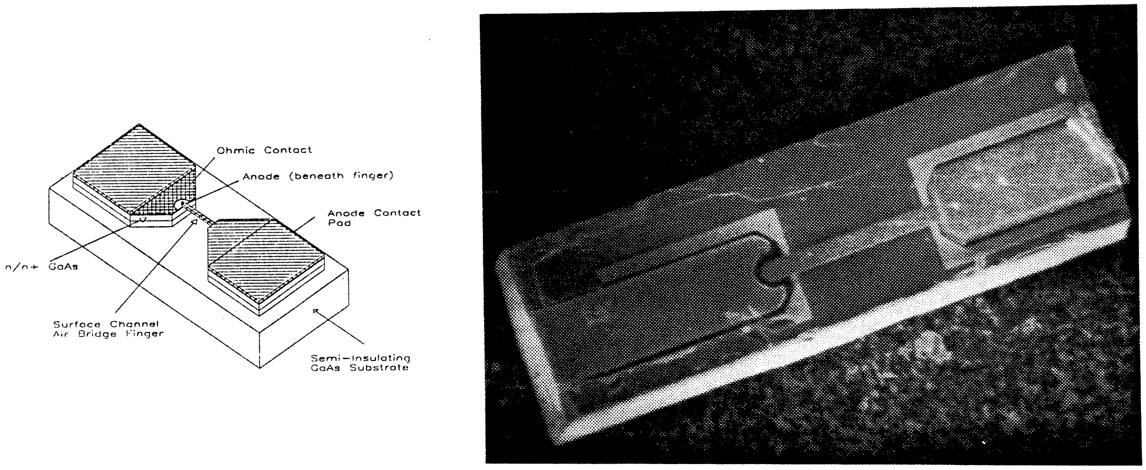

Fig. 1: SEM photo of SC6T2 varactor and sketch of the surface channel diode.

decreases at an output frequency of approximately 250 GHz. This indicates the SC6T2 diode may be most efficient at higher frequencies. New diodes will be fabricated which have higher junction capacitances, in an attempt to produce an improved match to the existing mount. Further evaluation will also be done to determine the optimum finger length at a given frequency for this multiplier. These RF results indicate that the SC6T2 is a comparable frequency multiplier to the 6P4 diode at millimeter wavelengths. However, the optimized RF performance will only be achieved when the planar diodes are used in a mount that is specifically designed for these devices.

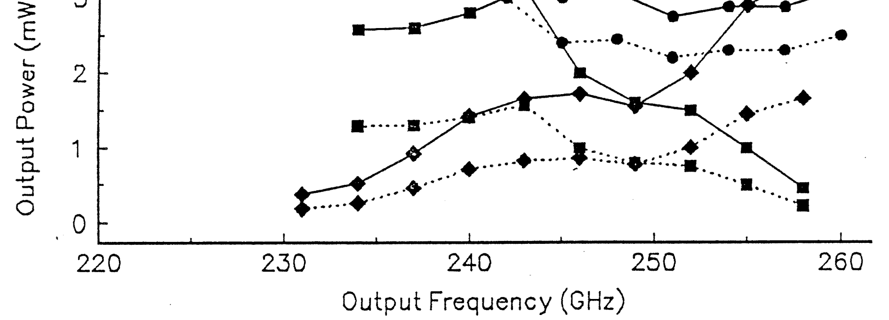

Fig. 2: SC6T2 RF performance.

III. PLANAR VARACTOR DIODES FOR BALANCED DOUBLING

In the proposed 1 THz multiplier chain, the first stage is a doubler from 80 to 160 GHz. This multiplier is designed to handle large input powers while remaining an efficient device so that it can generate as much power as possible to drive the second stage multiplier. A planar doubler chip has been developed that is based upon the balanced doubler of Erickson, which delivers up to 25 mW at 160 GHz using two whiskered varactor diodes [4].

The planar doubler chip consists of four GaAs Schottky varactor diodes, with a series diode pair for each leg of the balanced doubler. A scanning electron micrograph of the chip is shown in Fig. 3. Series diodes were used in an attempt to increase the power handling of the doubler chip, since the breakdown voltage of the diode pair is twice that of a single diode.

Four batches of doubler chips have been fabricated, and their design parameters and dc characteristics are listed in Table II. The junction capacitance of each diode was chosen so each series pair had approximately the same capacitance (20 fF) as the single whiskered diode used by Erickson. The first batch of diodes, designated SC10T1, had excessive series resistance and very large breakdown voltage. In the subsequent batches the doping density was increased and the epitaxial layer thickness decreased to reduce the device series resistance at the expense of lower breakdown voltage.

The SC10V2 diodes have been the most successful, and results of RF evaluation performed at 174 GHz by Dr. Erickson are presented in Fig. 4 [10,11]. The peak efficiency is 25% at an input power of 150 mW. The peak output power is 55 mW at an estimated input power of 250 mW. This maximum output power is more than twice the previous best doubler result at a similar frequency.

Generally, frequency multipliers tend to saturate in output at rather low power levels in the frequency range above 100 GHz. This saturation is believed to be due to the finite maximum carrier velocity in GaAs [12], which limits the displacement current in the diode. As a result, the efficiency tends to decrease rapidly above a critical power

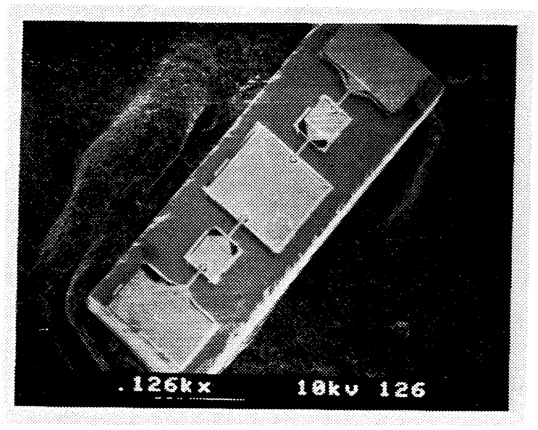

Fig.3: SEM photograph of the balanced doubler chip to 160 GHz.

Table II: Balanced Doubler Chip Characteristics

batch #	t_{chip} (μm)	t_{epi} (μm)	N_{epi} (cm^{-3})	diam. (μm)	C_T^* (fF)	diode pair R_s (ohms)	diode pair V_{bkdn} (V)
SC10T1	100	1.3	$1.8x10^{16}$	10	43	24	45
SC10T2	100	1.2	$2.5x10^{16}$	10	50	14	35
SC10V1	100	0.64	$4.5x10^{16}$	10	60	6	30
SC10V2	25	0.64	$4.5x10^{16}$	9	47	11	29

*C_T includes the junction capacitance and 9 fF fringing capacitance.

prior to reaching device breakdown. It can be seen from the data in Fig. 4, however that the efficiency of the planar balanced multiplier levels off for input powers above approximately 100 mW. This indicates that the velocity saturation effects are reduced by the series diode structure.

In the past, varactor diodes have been designed for maximum power handling by maximizing reverse breakdown voltage. It can be seen from Fig. 4, however that the SC10V2 series diodes can operate at more than twice the input power as the single 6P2 whiskered diodes, while having a modestly increased breakdown voltage (29 V for the diode pair compared to 20 V for the 6P2 diodes). It is now believed that current saturation, not breakdown voltage, is the major limitation on the amount of input power a varactor diode can handle.

Integrating diodes in series allows the area and number of diodes to be increased, while as far as the circuit design is concerened they may be treated as a single diode. A series combination of n identical diodes of individual area nA behaves the same as an nxn array of similar diodes which have individual area A. Therefore, the series array can handle n^2 times the power as a single diode (with area A) without increasing the current density or changing the impedance level.

Since the first stage multiplier has been very successful, work has begun on developing a planar chip for the doubler to 320 GHz. This multiplier will also be a balanced doubler and will be similar in structure to the 160 GHz device. A sketch of the new doubler chip is shown in Fig. 5. Since this multiplier will not have to handle as much power as the first stage, it can be optimized for high efficiency rather than power handling.

In our first attempt, the junction capacitance and chip size of the 160 GHz doubler structure will be scaled to operate at 320 GHz. Since the 320 GHz chip is much smaller (20 mils in length) than the 160 GHz chip (30 mils in length), the pad sizes must be significantly reduced. However, this will require improved ohmic contacts. Our standard SnNi/Ni/Au alloyed ohmic contact will be replaced by an evaporated Ni/Ge/Au ohmic contact which reliably obtains resistivities of $10^{-6}\Omega cm^2$. It is hoped that the first chips will be available for RF evaluation this spring.

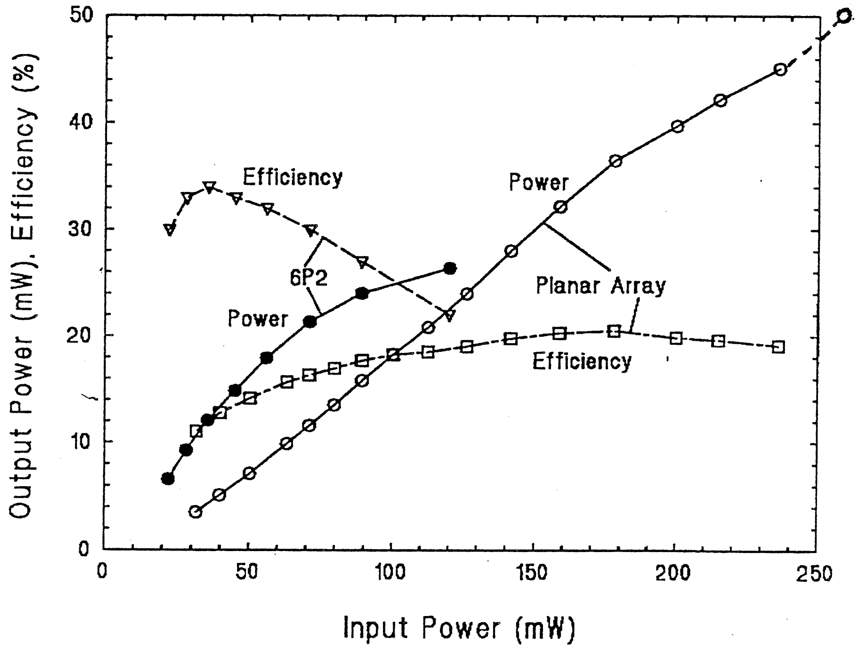

Fig. 4: RF data for the planar balanced doubler at 174 GHz.

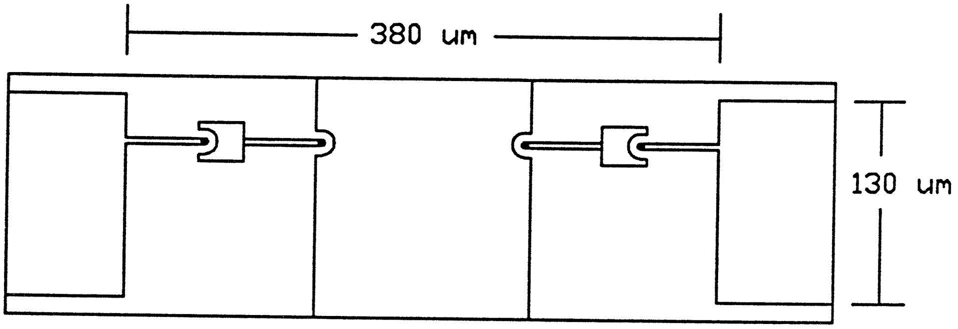

Fig. 5: Sketch of the prototype balanced doubler chip to 320 GHz.

IV. NOVEL VARACTORS

Several novel device structures are being investigated to determine their potential as frequency multipliers. In this section three of these devices are discussed. The integrated δ-doped varactor pair and the Schottky/two-dimensional-electron-gas (Schottky/2-DEG) are considered, and the numerical simulation of heterostructure barrier varactors is discussed.

Anti-Series δ-Doped Varactor Diode

A planar chip in which two δ-doped varactor diodes are integrated in an anti-series configuration has been designed to be used as a frequency tripler to 200-300 GHz. A scanning electron micrograph of the prototype chip is shown in Fig. 6. The anti-series pair produces a symmetric C-V characteristic, which offers significant benefits for tripling applications since an idler circuit at the second harmonic is not needed. The δ-doped varactor diodes have been shown to have a very sharp C-V characteristic [13,14] which is an advantage particularly at high frequencies where available input power is quite low.

C-V data for the prototype tripler chip is shown in Fig. 7. Each diode pair has a capacitance ratio ($C_{\max}/C_{\min}$) of approximately 1.8 and a breakdown voltage of 4.5 V. The zero-bias capacitance of the pair is approximately 38 fF, including 3 fF shunt capacitance. The results of an initial RF evaluation are shown in Fig. 2 along with the results for the SC6T2 diodes. The peak efficiency of the anti-series tripler is greater than 3% at about 243 GHz. The maximum power output of approximately 1.5 mW also occurs at this frequency. This preliminary data indicates that the prototype δ-doped tripler chip is a comparable frequency tripler to available whisker contacted diodes in the 200 GHz frequency range.

Design changes to improve device performance may include a lower active layer doping density than the present $2x10^{17} cm^{-3}$, and an increase in the active layer thickness to achieve a better capacitance ratio. Based upon the results of this research we hope to determine whether the anti-series δ-doped pair has the potential to be a high efficiency multiplier to 1 THz.

The Schottky/2-DEG Varactor Diode

The Schottky/2-DEG varactor diode is based on the lateral junction between the metal and the 2-dimensional electron gas [15-17], as shown in Fig. 8. In [17], we reported the C(V), the I(V) between 20-300K and the first millimeter wave multiplier measurements of the Schottky/2-DEG diode. These preliminary results were very

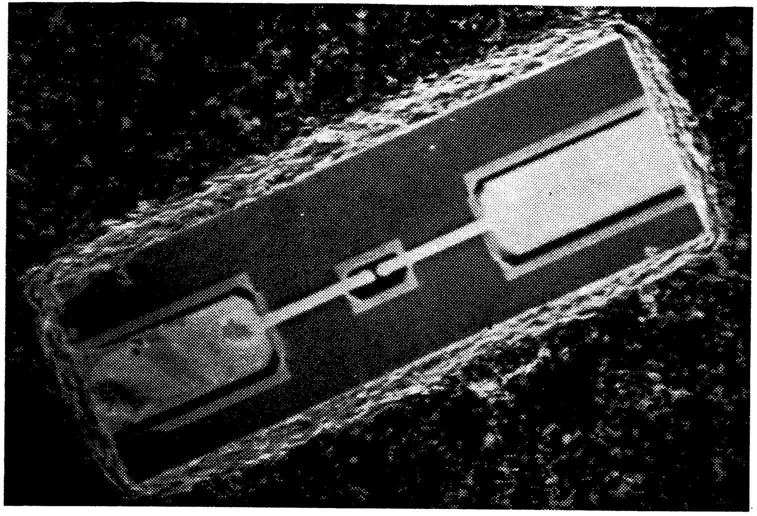

Fig. 6: SEM photograph of the prototype δ-doped tripler chip to 200 GHz

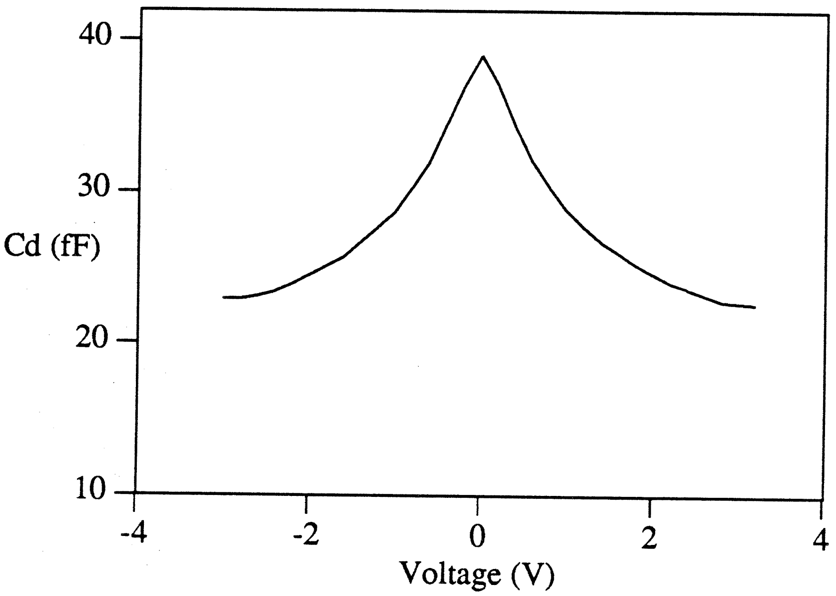

Fig. 7: C-V characteristic for δ-doped tripler chip to 200 GHz.

encouraging yet were unoptimized with regard to the series resistance and to the lack of a suitable planar diode multiplier mount for millimeter wavelengths. A new, more general theory for the C-V characteristic of the Schottky/2-DEG diode was also developed [18]. In this Section, we report recent progress in reducing the series resistance and briefly evaluate the potential performance of optimized devices. The new devices discussed here use the evaporated Ni/Au/Ge ohmic contact which should eventually yield lower resistance than the electroplated SnNi/Ni/Au contact.

The series resistance of the Schottky/2-DEG diode is due primarily to the sheet resistance of the undepleted 2-dimensional electron gas (Fig. 8) and to the ohmic contact resistance. The sheet resistance of the pseudomorphic AlGaAs/InGaAs material used to date is approximately 500 Ω / □ (100 Ω / □) at 300K (77K). Recent devices having 1 micron channel length and 90 micron channel width were evaluated at room temperature. The lowest series resistance measured was 9 Ω from which we deduce the ohmic contact resistance to be about 0.4 Ω-mm. This is the first Schottky/2-DEG diode batch fabricated using the evaporated Ni/Ge/Au ohmic contact which is still being optimized. From the literature, we expect to achieve 0.1-0.2 Ω-mm ohmic contact resistivity. Thus we expect to significantly reduce the series resistance in future devices.

The C-V characteristic of the $L = 1\ \mu m$, $W = 90\ \mu m$ device is shown in Fig. 9 (squares). Also shown is the C-V characteristic of the $L = 3\ \mu m$, $W = 80\ \mu m$ device (diamonds) reported in [17]. We measured the shunt capacitance of 19 fF for the new devices by etching away the 2-DEG in the channel. Thus, the zero-bias junction capacitance is approximately 22-25 fF/100 μm, whereas for punch-through limited devices, the minimum capacitance is nearly equal to the shunt capacitance.

A single room temperature millimeter wave tripler measurement of the 1 micron channel length device was made using the NRAO tripler (described in [9]), which was designed for whisker-contacted diodes. The multiplier measurements are shown in

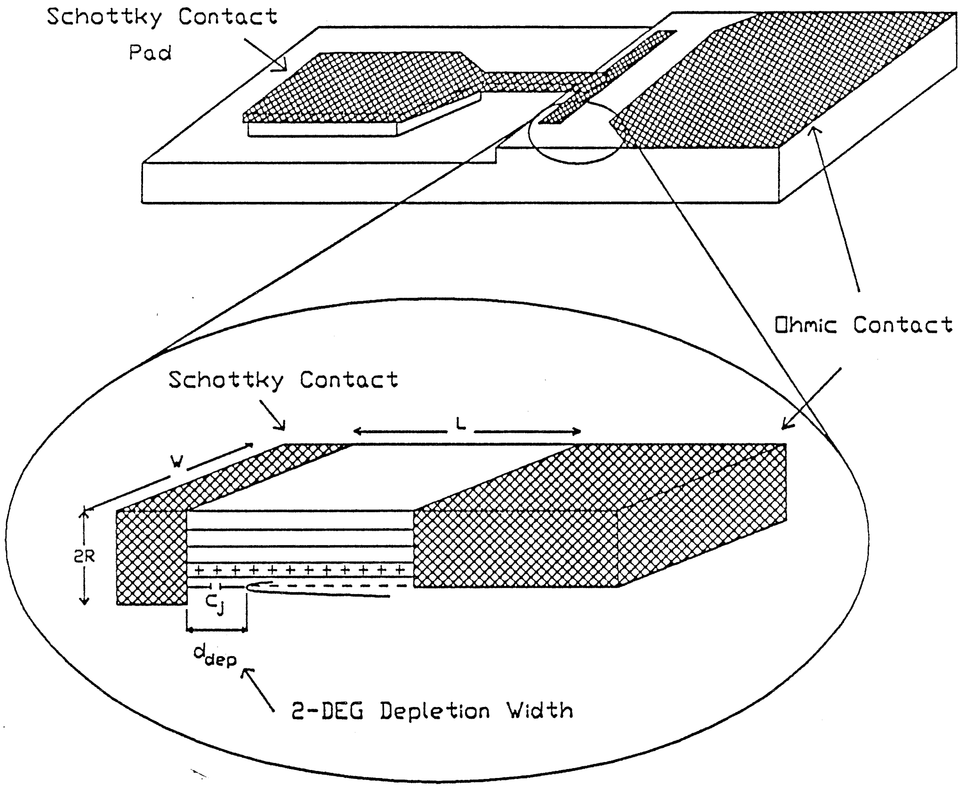

Fig. 8: Sketch of the Schottky/2-DEG multiplier diode.

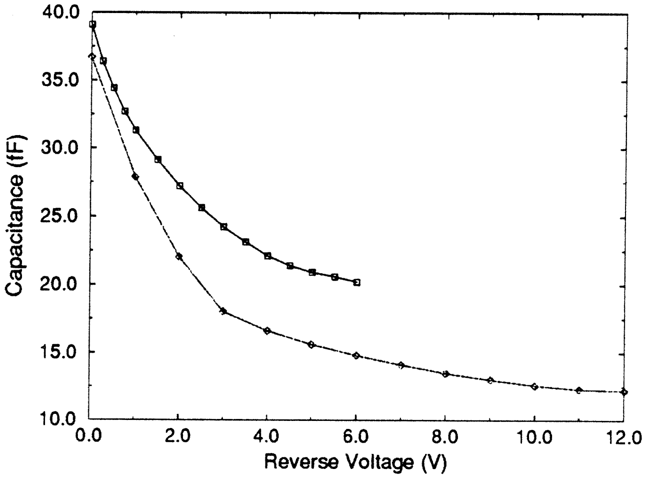

Fig. 9: *C-V characteristic of the 1 μm length, 90 μm width Schottky/2-DEG diode (squares). Also shown is the C-V characteristic of the 3 micron length, 80 micron width device (diamonds) reported in [16].*

Fig. 10. The output power at 225 GHz was 355 μ*W* with 50 mW input for an efficiency of 0.7 percent, compared with 186 μW measured previously [17] on longer channel devices. The higher efficiency is due either to a better impedance match between the diode and the multiplier or to the lower series resistance, or both. However, it is not clear whether significantly higher efficiency can be achieved using this multiplier mount.

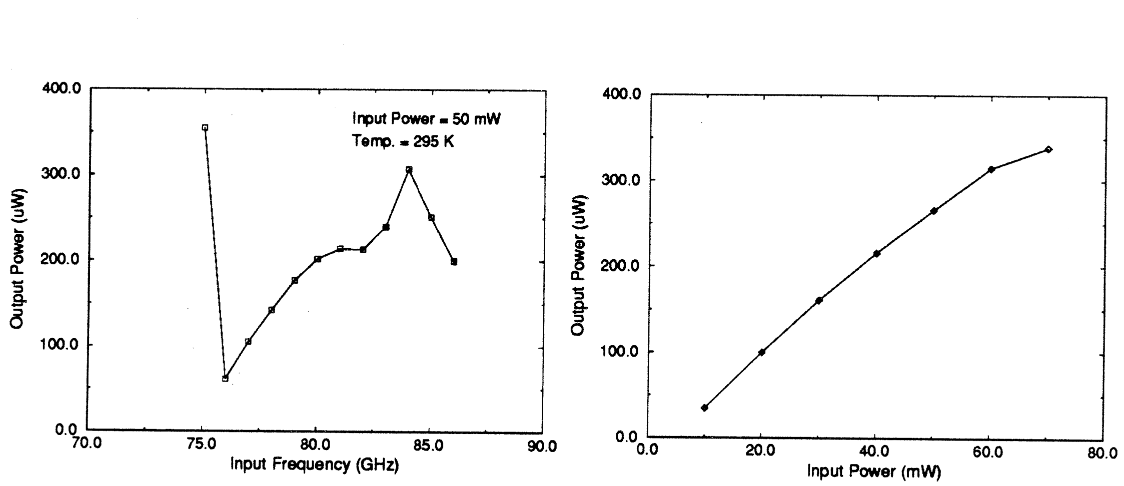

Fig. 10: Output power versus input frequency (left) and input power at 84 GHz (right) for the 1 micron length Schottky/2-DEG diode at room temperature.

The optimization of the Schottky/2-DEG diode for millimeter wave applications will focus on device designs which are suitable for insertion into the planar balanced doubler discussed in Section III. In this multiplier, the impedance match between the diodes and the multiplier circuit was excellent and the doubler performance was outstanding. A Schottky/2-DEG varactor, made using the present heterostructure material to have a similar capacitance range as each diode in the balanced doubler, would have a channel width of about 150 μm and a channel length of 1 μm. The series resistance of this device, assuming an ohmic contact resistance of 0.2 Ω-mm, would be about 2 Ω (5 Ω) at 77K (300K), compared with about 6 Ω for the standard balanced doubler. The breakdown voltage would be about 10 V compared to the 15 V breakdown of the standard balanced doubler, however, it appears this will be sufficient assuming reasonable input power levels. Thus we expect comparable performance of the Schottky/2-DEG diode at room temperature and superior performance at low temperatures.

Heterostructure Barrier Varactors

The Heterostructure Barrier Varactor (HBV) is an attractive alternative to Schottky barrier varactors for frequency multiplication in the millimeter to submillimeter wavelength ranges. A single barrier HBV consists of a high band gap semiconductor sandwiched between symmetric capacitive modulation regions of lower band gap material such that the device has an evenly symmetric nonlinear capacitance-voltage (C-V) relationship. The evenly symmetric C-V characteristic eliminates the even harmonic components of the current waveform yielding more efficient third harmonic frequency multipliers. By epitaxially stacking many single barrier HBVs, high device cut-off frequencies with moderate breakdown voltages are attainable. Also, superior device reliabilties are expected for stacked HBVs since the terminal voltage is distributed over multiple barriers. HBVs have an added advantage over Schottky barrier varactors in that the semiconductor alloy composition and doping profiles, as well as the barrier thickness, device area, and the number of barriers can be independently varied to achieve the optimum C-V characteristic. Thus, the C-V characteristic can be designed to simultaneously achieve optimum third harmonic operation and optimum device/circuit matching. Ultimately, this should yield a very efficient single device with potentially higher power generation capabilities compared to multiple Schottky diode multiplier configurations.

With this in mind, the overall goal of our HBV research is to develop a fully self-consistent time-dependent (AC) simulator for GaAs/InGaAs/AlGaAs HBVs such that the device geometry, doping profile, and alloy composition profile can be chosen for optimal circuit performance. Our present discussion focuses on the details of the numerical device time-independent (DC) simulator that is used to predict the nonlinear I-V characteristics of GaAs/InGaAs/AlGaAs HBV structures.

The numerical DC simulator is based on the Alloy Ramp Diode DC simulator developed by Tait [19]. Any combination of abrupt heterojunctions and alloy ramps in the GaAs/InGaAs/AlGaAs material system can be simulated. Carrier transport through the device is modeled using the one-dimensional semiconductor drift-diffusion equations for electrons cast such that the state variables are the electron current $J_n(x)$, electron quasi-fermi level $\phi_n(x)$, electrostatic potential $\psi(x)$, and displacement vector $D(x)$. These equations are

$$\begin{gathered}
dJ_n / dx = 0 \\
d\phi_n / dx = (-J_n / \mu_n(x)\, n_i)\ \exp\,(-\psi(x) - V_n(x) + \phi_n(x)) \\
d\psi / dx = -D(x) / \varepsilon_r(x) \\
d(D(x)) / dx = N_D(x) - n_i\ \exp\,(\psi(x) + V_n(x) - \phi_n(x))
\end{gathered}$$

where $\mu_n(x)$ is the material-dependent electron mobility, n_i is the intrinsic electron concentration in GaAs, $\varepsilon_r(x)$ is the material-dependent relative permittivity, and $V_n(x)$ is the alloy potential relative to GaAs [20]. The carrier transport equations are solved in two steps. First, the thermal equilibrium values of the state variables are obtained from the discretized nonlinear Poisson equation using a globally convergent nonlinear iterative technique [21]. The carrier transport equations are then solved using a finite-difference discretization scheme over a non-uniform mesh via the Newton-Raphson method with the thermal equilibrium solution serving as the starting point for the method. The given state variable set and the formulation of the drift-diffusion state equations as first-order differential equations has been chosen because of their superior accuracy and convergence properties when combined with the chosen numerical solution method [19].

In order to accurately predict the current across the abrupt heterointerfaces of an HBV, thermionic-emission of carriers over the barrier is included in the model via appropriate current boundary conditions at the abrupt heterointerfaces [19]. The thermionic-emission boundary condition reduces to an electron "fluid-outflow" boundary condition under appropriate biasing conditions, i.e. at the right heterointerfaces in Figures 11a and 11b. Tunneling through the barrier is modeled by reducing the barrier height. The effective barrier height reduction is calculated from the WKB approximation for tunneling through the tip of a triangular barrier [22]. For the present discussion, we restrict ourselves to a single barrier HBV such that solutions to the drift-diffusion equations are found in the three regions of the device after the domain of the original HBV is "folded". This yields a total of ten carrier transport equations with both ohmic and heterointerface boundary conditions imposed at both domain boundaries.

The GaAs and AlGaAs material parameters required for the model are taken from several sources including Adachi [23], Blakemore [24], Saxena [25], and Tait [19]. Of particular importance for the GaAs/AlGaAs material system is the Γ conduction band offset of 60% which yields a conduction band discontinuity of 235 meV for a $GaAs/Al_{0.7}Ga_{0.3}As$ heterointerface. The InGaAs material parameters required for the model are taken from several sources including Adachi [26] and Pearsall [27]. It is assumed that all InGaAs layers of interest are coherently strained such that the strain correction to the energy gap calculated by Anderson [28] is valid. For the AlGaAs/InGaAs material system the Γ conduction band offset is 55% [29] which yields a conduction band discontinuity of 376 meV for a pseudomorphic $In_{0.2}Ga_{0.8}As/Al_{0.7}Ga_{0.3}As$ heterointerface.

The simulated devices consisted of a 215 A undoped ($1x\,10^{14}cm^{-3}$) $Al_{0.7}Ga_{0.3}As$ barrier surrounded by 55 A undoped ($1x\,10^{14}cm^{-3}$) spacer layers ($GaAs$ or $In_{0.2}Ga_{0.8}As$) and 1500 A doped ($1x\,10^{17}cm^{-3}$) modulation layers ($GaAs$, or 1000 A $GaAs$ with 500 A graded $In_{0.0-0.2}Ga_{1.0-0.8}As$). For all simulations, A* was taken to be $0.15\ A/K^2cm^2$ for the $Al_{0.7}Ga_{0.3}As$ barrier [30], the electron mobility in the barrier was taken to be $2000cm^2/Vs$, the electron mobility elsewhere was taken to be $4000cm^2/Vs$, and barrier tunneling was assumed to occur via the AlGaAs X conduction band where the relevant electron effective mass is the transverse effective mass of $0.202m_o$. The WKB tunneling probability was assumed to be e^{-1} for all structures simulated.

Figure 11 shows typical band structure diagrams for a $GaAs/Al_{0.7}Ga_{0.3}As$ HBV and a $GaAs/In_{0.0-0.2}Ga_{1.0-0.8}As/In_{0.2}Ga_{0.8}As/Al_{0.7}Ga_{0.3}As$ HBV biased at 0.25 V. As indicated in the figure, the $GaAs/In_{0.0-0.2}Ga_{1.0-0.8}As/In_{0.2}Ga_{0.8}As/Al_{0.7}Ga_{0.3}As$ structure has an appreciably larger abrupt barrier as well as an alloy ramp. The simulated I-V relationship for the GaAs/AlGaAs structures is shown in Figure 12 along with the experimental data of Nilsen et al. [31] for diodes having an area of 625 μm^2. The simulated I-V relationship for diodes with graded InGaAs layers and $A^*=0.15\ A/K^2cm^2$ showed significantly reduced currents over the same bias range due to the increased barrier height. However, it is not clear what value of A* should be used for such a structure since strain effects significantly alter the band structure of the InGaAs and could significantly alter A*.

V. SUMMARY

Whisker contacted Schottky barrier varactor diodes have proven to be very reliable and effective multiplier elements for millimeter and submillimeter wavelength applications. However, planar varactor diodes offer improved performance and reliability. Improvements in chip design have made the prototype planar Schottky varactors competitive to whiskered diodes at millimeter wavelengths. By integrating several diodes on a single chip, increased power handling ability has been achieved with the integrated balanced doubler. This balanced doubler design is now being scaled to produce a doubler to 320 GHz.

Several novel device technologies have also been reviewed as possible multiplier elements. The anti-series δ-doped varactor diode produces a symmetric C-V characteristic which is beneficial for tripling applications. Prototype devices have shown promising initial results, and their potential as a tripler to 1 THz is being evaluated. The 2-DEG/Schottky diode benefits from increased electron mobility, and has shown promise

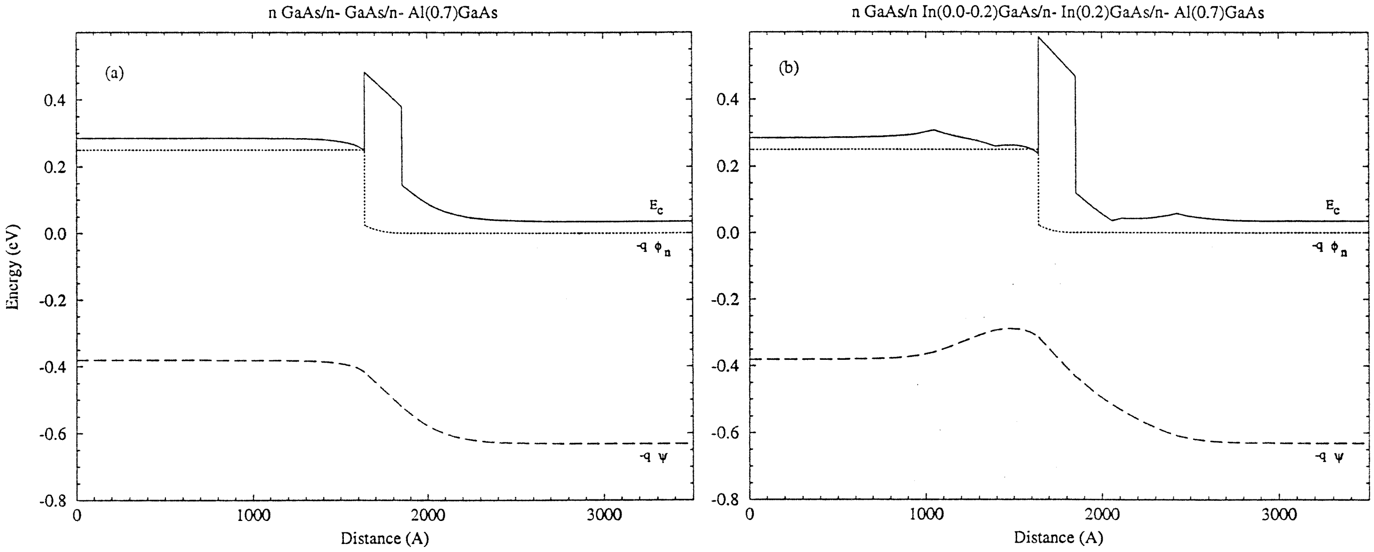

Fig. 11: Band structure of a $GaAs/Al_{0.7}Ga_{0.3}As$ *HBV (a) and a* $GaAs/In_{0.2}Ga_{0.8}As/Al_{0.7}Ga_{0.3}As$ *HBV (b) biased at 0.25 V.*

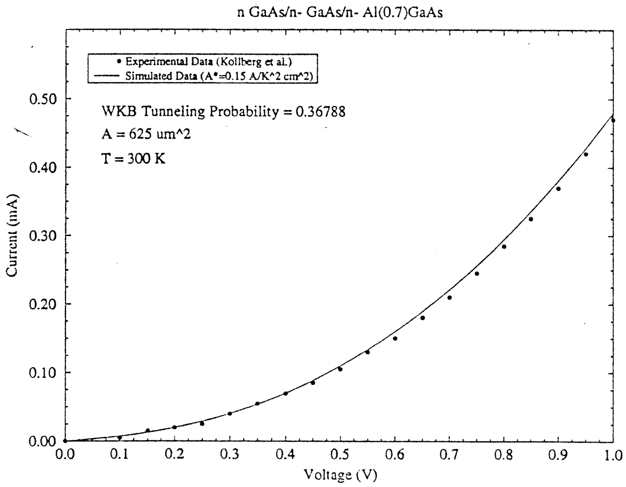

Fig. 12: Simulated I-V curve for the HBV of Figure 11a. Experimental data is taken from Nilsen et al. [31].

as a millimeter wave multiplier element. The device structure is now being optimized for reduced series resistance. Heterostructure barrier varactors show promise in high frequency multiplier applications, and a numerical model to simulate their I-V and C-V characteristics is being developed. Fabrication of initial HBV devices in the GaAs/AlGaAs and GaAs/InGaAs/AlGaAs material systems has begun. One of the main problems in producing optimum performance for the novel multipliers, is that the best RF performance will not be achieved until mounts specifically designed for these devices are made available.

It is our goal to develop a multiplier chain to 1THz suitable for space applications using planar technology. The first step is the high-power doubler which has produced record output power at 174 GHz. For the first time a planar device has displayed superior performance to a whisker contacted multiplier. This not only shows the great potential for diode arrays as frequency multipliers, but also for planar varactor diodes in general.

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REFERENCES

[1] R. Zimmermann, R. Zimmermann and P. Zimmermann, "All Solid-State Radiometers for Environmental Studies to 700 GHz," Third Int'l Symp. Space THz Tech., Ann Arbor, MI, March 1992.

[2] H. Nett, S. Crewell, K. Kunzi, "A 625-650 GHz Heterodyne Receiver for Airborne Operation," 16th Int'l Conf. IR and MM Waves, Lausanne, Switzerland, August 1991.

[3] S. Crewell and H. Nett, "Measurements of the Single Sideband Suppression for a 650 GHz Heterodyne Receiver," Third Int'l Symp. Space THz Tech., Ann Arbor, MI, March 1992.

[4] N.R. Erickson, "High Efficiency Submillimeter Frequency Multipliers," 1990 IEEE MTT-S Int'l Microwave Symp., Dallas, TX, May 1990.

[5] A. Rydberg, B.B. Lyons and S. Lidholm, "On the Development of a High Efficiency 750 GHz Frequency Tripler for THz Heterodyne Systems," IEEE Trans. Microwave Theory Tech., Vol. MTT-40, No. 5, pp. 827-830, May 1992.

[6] W.L. Bishop, K. McKinney, R.J. Mattauch, T.W. Crowe and G. Green "A Novel Whiskerless Schottky Diode for Millimeter and Submillimeter Wave Applications," Proc. 1987 IEEE MTT-S Intl. Symp., Las Vegas, NV, 607-610, June 1987.

[7] W.L. Bishop, T.W. Crowe, R.J. Mattauch and P.H. Ostdiek, "Planar Schottky Barrier Mixer Diodes for Space Applications at Submillimeter Wavelengths," Microwave and Optical Technology Lett., Special Issue on Space THz Tech., Vol. 3, No. 1, pp. 44-49, Jan. 1991.

[8] W.L. Bishop, E.R. Meiburg, R.J. Mattauch and T.W. Crowe, "A Micron Thickness, Planar Schottky Barrier Diode Chip for Terahertz Applications with Theoretical Minimum Parasitic Capacitance," 1990 IEEE MTT-S Int. Microwave Symp., Dallas, TX, May 1990.

[9] R. Bradley, "The Application of Planar Monolithic Technology to Schottky Varactor Millimeter-wave Frequency Multipliers," Ph.D. Thesis, University of Virginia, May, 1992.

[10] B.J. Rizzi, T.W. Crowe and N.R. Erickson, "A High Power Millimeter Wave Frequency Doubler Using a Planar Diode Array," Accepted for Publication, 1993 IEEE MTT-S Microwave and Guided Wave Letters.

[11] N.R. Erickson, B.J. Rizzi and T.W. Crowe, "A 174 GHz High Power Doubler Using a Planar Diode Array," Fourth Int'l Symp. Space THz Tech., Los Angeles, CA, March 1993.

[12] E.L. Kollberg, T.J. Tolmunen, M.A. Frerking and J.R. East, "Current Saturation in Submillimeter Wave Varactors," IEEE Trans. Microwave Theory Tech., Vol. MTT-40, No.5, pp. 831-838, May 1992.

[13] B.J. Rizzi, T.W. Crowe and W.C.B. Peatman, "A δ-Doped Varactor Diode for Submillimeter Wavelengths, "Digest of the 15th Int'l Conf. on IR and MM Waves, pp. 478-480, Orlando, Dec. 1990.

[14] T.W. Crowe, W.C.B. Peatman and W.L. Bishop, "GaAs Schottky Barrier Diodes for Space Based Applications at Submillimeter Wavelengths," The First Int'l Symp. Space THz Tech.

Proceedings, pp. 256-272, Ann Arbor, MI, March 1990.

[15] W.C.B. Peatman, T.W. Crowe and M. Shur, "Design and Fabrication of Heterostructure Varactor Diodes for Millimeter and Submillimeter Wave Multiplier Applications," Proc., IEEE/Cornell Conf. on Advanced Concepts in High Speed Semic. Dev. and Circuits, Ithaca, NY, pp. 49-57, August 1991.

[16] W.C.B. Peatman, T.W. Crowe and M. Shur, "A Novel Schottky/2-DEG Diode for Millimeter and Submillimeter Wave Multiplier Applications," *IEEE Electron Device Lett.*, Vol. 13, No. 1, pp. 11-13, January 1992.

[17] W.C.B. Peatman, T.W. Crowe, M. Shur and B. Gelmont, "A Schottky/2-DEG Varactor Diode for Millimeter and Submillimeter Wave Multiplier Applications," Proc. Third Int'l. Symp. on Space THz Tech., Ann Arbor, MI, pp. 93-109, March 24-26, 1992.

[18] B.L. Gelmont, W. Peatman, and M. Shur, "Heterodimensional Schottky Metal-Two Dimensional Electron Gas Interfaces," 20th Conf. Physics and Chem. of Semic. Interfaces, Williamsburg, VA, Jan. 25-29, 1993, also to be published in J. Vac. Sci. Tech. B, July/Aug. 1993.

[19] G. B. Tait, "Electron Transport in Rectifying Semiconductor Alloy Ramp Heterostructures," PhD Dissertation, The Johns Hopkins University, 1992.

[20] M. S. Lundstrom and R. J. Schuelke, "Numerical Analysis of Heterostructure Semiconductor Devices," IEEE Trans. Electron Devices, Vol. ED-30, No. 9, pp. 1151-1159, 1983.

[21] G. B. Tait, "Heterostructure Semiconductor Device Analysis: A Globally Convergent Solution Method for the Nonlinear Poisson Equation," Solid-State Electron., Vol. 32, No. 5, pp. 369-376, 1989.

[22] E. H. Rhoderick and R. H. Williams, "Metal-Semiconductor Contacts, 2nd Edition," Oxford, England: Claredon, 1988.

[23] S. Adachi, "GaAs, AlAs, and AlGaAs: Material Parameters for Use in Research and Device Applications," J. Appl. Phys., Vol. 58, No. 3, pp. R1-R29, 1985.

[24] J. S. Blakemore, "Semiconducting and Other Major Properties of Gallium Arsenide," J. Appl. Phys., Vol. 53, No. 10, pp. R123-R181, 1982.

[25] A. K. Saxena, Phys. Status Solidi (b), Vol. 105, p. 777, 1981.

[26] S. Adachi, "Material Parameters of InGaAsP and Related Binaries," J. Appl. Phys., Vol. 53, No. 12, pp. 8775-8792, 1982.

[27] T. P. Pearsall (ed.), "GaInAsP Alloy Semiconductors," New York, N.Y.: John Wiley & Sons, Inc., pp. 456-457, 1982.

[28] N. G. Anderson, "Strained-Layer InGaAs-GaAs Heterojunctions, Quantum Wells, and Superlattices: Electronic Structure and Optical Properties," PhD Dissertation, North Carolina State University, 1988.

[29] D. C. Bertolet, J. Hsu, S. H. Jones, and K. M. Lau, "Pseudomorphic GaAs/InGaAs Single Quantum Wells by Atmospheric Pressure Organometallic Chemical Vapor Deposition," Appl. Phys. Lett., Vol. 52, No. 4, pp. 293-295, 1988.

[30] P. M. Solomon, S. L. Wright, and C. Lanza, "Perpendicular Transport Across (Al,Ga)As and the G to X Transition," Superlatt. Microstruc., Vol. 2, No. 6, pp. 521-525, 1986.

[31] S. M. Nilsen, H. Gronqvist, H. Hjelmgren, A. Rydberg, and E. L. Kollberg, "Progress on Single Barrier Varactors for Submillimeter Wave Power Generation," Third Int. Symp. Space THz Tech., Ann Arbor, MI, March 1992.