THEORETICAL EFFICIENCY OF MULTIPLIER DEVICES

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Abstract

During the past few years, several new devices have been proposed for use in frequency multipliers at millimeter and submillimeter wavelengths. Candidate diodes include a quantum well diode, a single barrier varactor, a barrier-intrinsic-N diode, a delta-doped varactor and a high electron mobility varactor. In comparison to the conventional Schottky varactor, these new diodes have some potential advantages in their characteristics, such as a stronger nonlinearity or a special-symmetry, which make them very attractive for millimeter and submillimeter wave frequency multiplication. This paper gives an overview of these novel devices and their potential benefits in comparison to the conventional Schottky-barrier varactor. Their performance has been analyzed theoretically in various low and high order multipliers for 200 GHz and 1 THz.

Introduction

Basic scientific research including radio astronomy, remote sensing of the atmosphere, plasma diagnostics and laboratory spectroscopy has long been the primary application for shorter millimeter and submillimeter wave technology. More recently this spectral range is also being considered for space-borne radar and communication systems. Fundamental local oscillator sources available today for low-noise heterodyne receiver systems include tube oscillators, gas lasers and solid-state sources. The tube oscillators and lasers can cover frequencies well above 1 THz, but especially for space-borne applications, these sources require considerable improvement to reduce size or to increase lifetime and reliability. Solid-state sources such as Gunn oscillators do not have these disadvantages, but operate only up to about 200 GHz. Therefore, frequency multipliers are needed to achieve higher frequencies.

The standard "workhorse", the GaAs Schottky-barrier varactor multiplier, is extensively used for signal generation at millimeter and submillimeter wavelengths. Although there are still some incomplete areas in the study and optimization of this diode, such as the behaviour of the C-V characteristics close to the built-in potential or the effect of multiplier cooling, the Schottky varactor has shown to be an efficient device, both theoretically and experimentally [1,2] at millimeter and lower submillimeter wavelengths. However, considerable improvement is still required at frequencies over 500 GHz in order to fulfill input power requirements of mixer devices.

While standard Schottky varactor technology is still maturing, several novel diodes have been proposed for use as multipliers at millimeter and submillimeter wavelengths. These diodes include a quantum well diode [3], a single barrier varactor [4], a BIN diode (barrier-intrinsic-n^+) [5], a delta-doped varactor [6] and a high electron mobility varactor [7].

In comparison to the Schottky varactor, these new diodes have some potential advantages in their characteristics, such as a stronger nonlinearity or a special-symmetry, which make them very attractive for millimeter and submillimeter wave frequency multiplication. Stronger nonlinearities allow more efficient harmonic generation with smaller input signal levels, and more efficient higher-order harmonic generation with unoptimized idler terminations.

By using a device having a symmetric C-V curve or an antisymmetric I-V curve, only odd-harmonics are generated. Therefore, there is no need for an idler termination in the case of a frequency tripler. Similarly a frequency quintupler requires only one idler termination at the 3rd harmonic for optimum operation. Schottky varactors, or other devices, having asymmetric curves generally require an idler termination at each intermediate harmonic frequency.

This paper gives a brief overview of these novel diodes and their theoretical performance as multipliers at millimeter and submillimeter wavelengths. All of these diodes are considerably less mature than the conventional Schottky varactor. Therefore, there should be opportunity for device optimization for each application.

Devices

The quantum well diode (QWD) has been the subject of theoretical and experimental studies since 1970 [8]. Its high speed [9] and the negative differential resistance make it attractive for millimeter-wave oscillators and its highly nonlinear antisymmetric *I-V* curve is suitable for frequency multiplication. The quantum well diode has a thin (20–60 Å) undoped layer (well) sandwiched between two thin barriers (10–50 Å) of material having a larger band-gap than the well (Fig. 1a). This structure acts as a resonator which exhibits peaks in electron transmission (current) at certain values of incident electron energy (voltage). Therefore, the QWD has regions of negative differential resistance when the voltage is just greater than the resonance.

In addition to a voltage-dependent resistance (Fig. 1b), the quantum well diode has a highly nonlinear capacitance related to the epitaxial layers exterior to the barriers. Under the assumption that no current flows through the device, the capacitance can be approximated as

$$C = \frac{C_0}{1 + \sqrt{(2\epsilon/qN_d w^2)|V_j|}}, \qquad C_0 = \frac{\epsilon A}{w}, \tag{1}$$

where C_0 is the zero-bias capacitance, which depends on the diode area A and the total thickness of the double barrier structure w ($w = 2w_{barrier} + w_{well}$); ϵ is the dielectric constant, q is the electron charge, N_d is the doping concentration outside the barriers and V_j is the junction voltage. If the epitaxial layer width and doping concentration is equal in both sides of the double barrier structure, the *C-V* curve is symmetric and can generate only odd harmonics without external biasing. Quantum well diodes have been demonstrated as a tripler to 200 GHz [10]. The tripling mechanism has since been determined to be the nonlinear *C-V* characteristic rather than the *I-V* characteristic. Recent capacitance measurements of the quantum-well diodes have revealed that the *C-V* curve is less nonlinear at small voltages and exhibits an extra peak in the capacitance at voltages close to the negative differential resistance (Fig. 1c) [11].

Theoretically the resistive multiplication is far less efficient than the reactive and it often merely decreases the device performance as a multiplier. Therefore, it is reasonable to suppress the effects of the nonlinear resistance, if this is possible. The structure of the quantum well diode can be modified by replacing the well and dual barriers with a single barrier which is thick enough (150–200 Å) for suppressing the current flow through the device. The resulting diode, a single barrier varactor (SBV) [4], has a theoretical capacitance which is symmetric and follows Eq. (1) (Fig. 1c). This makes the SBV (also called quantum

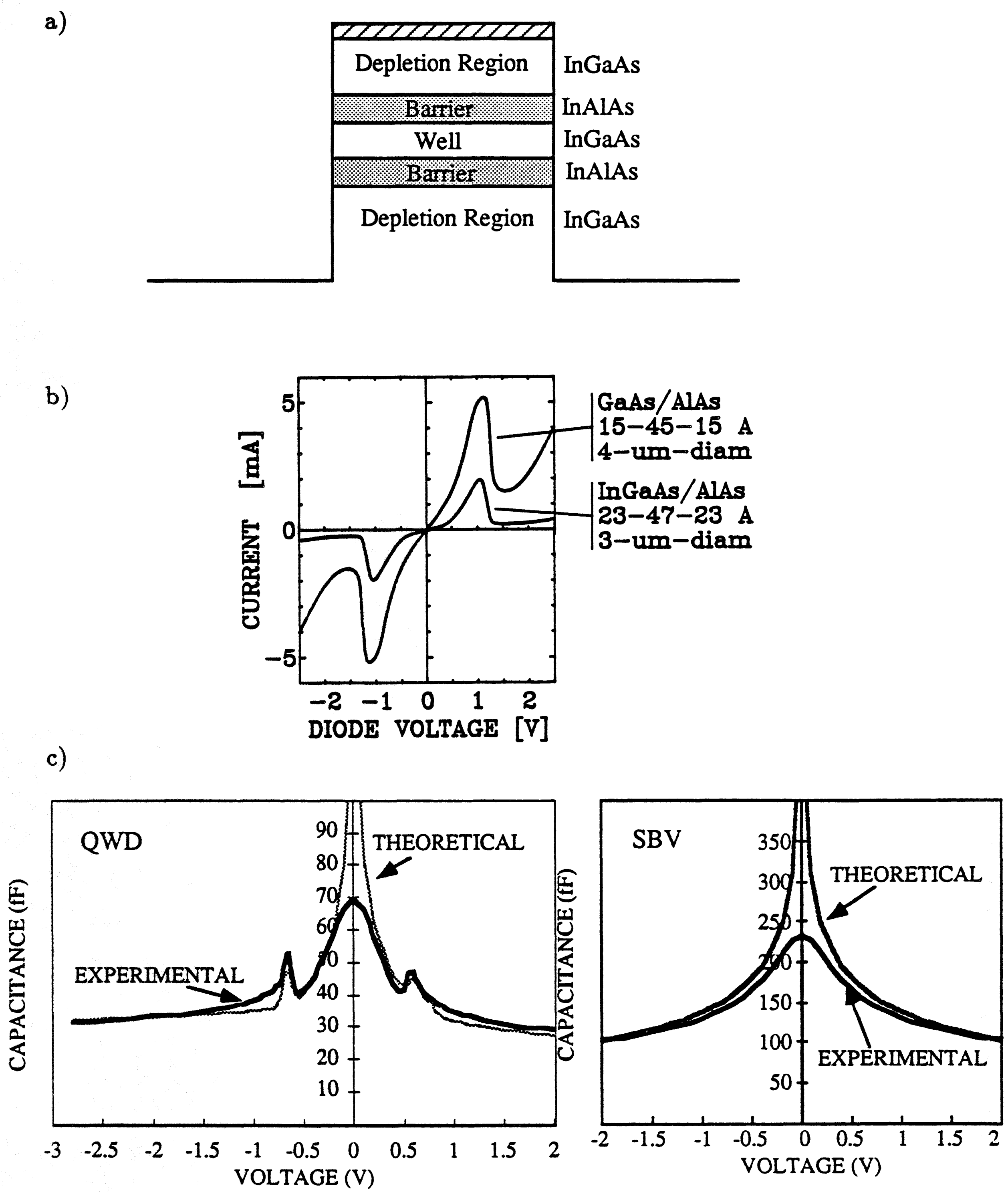

Figure 1. **a)** Structure of the quantum well diode. In a single barrier varactor only one barrier is used between epitaxial layers. This barrier is made thick enough in order to suppress the current flow through the device. **b)** Examples of measured *I-V* curves of quantum well diodes. **c)** Theoretical and experimental *C-V* curve of a quantum well (left) and a single barrier varactor diode (right). The theoretical curve of the quantum well diode is based on a more detailed model which takes into account current flow through the device.

barrier varactor, QBV) very attractive in millimeter wave multiplier applications.

The Barrier-Intrinsic-N (BIN) diode has been proposed as an improved varactor diode for harmonic multiplication [5]. Unlike quantum well diodes or single barrier varactors which consist of a heterostructure and two ohmic contacts as terminals, the BIN diode is essentially a Schottky varactor with an unique doping profile that yields a sharper C-V characteristic. The diode consists of a Schottky-contact, a barrier layer (thickness d_1), a sheet doping layer and an intrinsic layer (thickness d_2) on a highly doped substrate (Fig. 2a). Generally, the diode may be designed so that at zero or low reverse bias, the sheet doping layer is just barely depleted and the capacitance is

$$C_{max} \approx \frac{\epsilon A}{d_1}. \tag{2}$$

As the reverse voltage increases the depletion region switches to $d_1 + d_2$. Because further increase of the bias has no effect on the capacitance due to the high doping of the substrate, the minimum capacitance can be expressed as

$$C_{min} \approx \frac{\epsilon A}{d_1 + d_2}. \tag{3}$$

Therefore, a single BIN diode has an asymmetric C-V curve (Fig. 2b) which is sharper than that of the Schottky varactor. By contacting two diodes back-to-back, a symmetric "pulse"-like curve results (Fig. 2c). More importantly, the back-to-back BIN is an inherently planar device having both terminal contacts on the same surface. This is an advantageous feature, especially for space-borne applications.

Due to the intrinsic layer, the series resistance of the BIN diode is relatively high, which results in a low cut-off frequency. In a modification of the BIN diode, the BNN (barrier-n-n^+) or delta-doped varactor structure [6,12], a moderately-doped layer is used instead of the intrinsic layer to decrease the resistance in the undepleted epitaxial layer.

A high electron mobility varactor is another inherently planar diode which incorporates the proven performance of a standard Schottky varactor technology with the electron properties of the two-dimensional electron gas formed, e.g in a GaAs/AlGaAs heterostructure. In these structures the electrons have higher mobility than in conventional varactors, especially if the device is cooled [7]. The high electron mobility varactor consists of a Schottky-contact followed by a two-dimensional electron gas (2-DEG) modulation region (Fig. 3). By applying a reverse bias to the anode contact, the 2-DEG in the modulation region will become depleted near the Schottky-contact, reducing contact capacitance. As the bias is further increased, more of the layer will be depleted. The geometry of the structure results in a sheet-like variable capacitor which has an inversely logarithmic dependence on voltage.

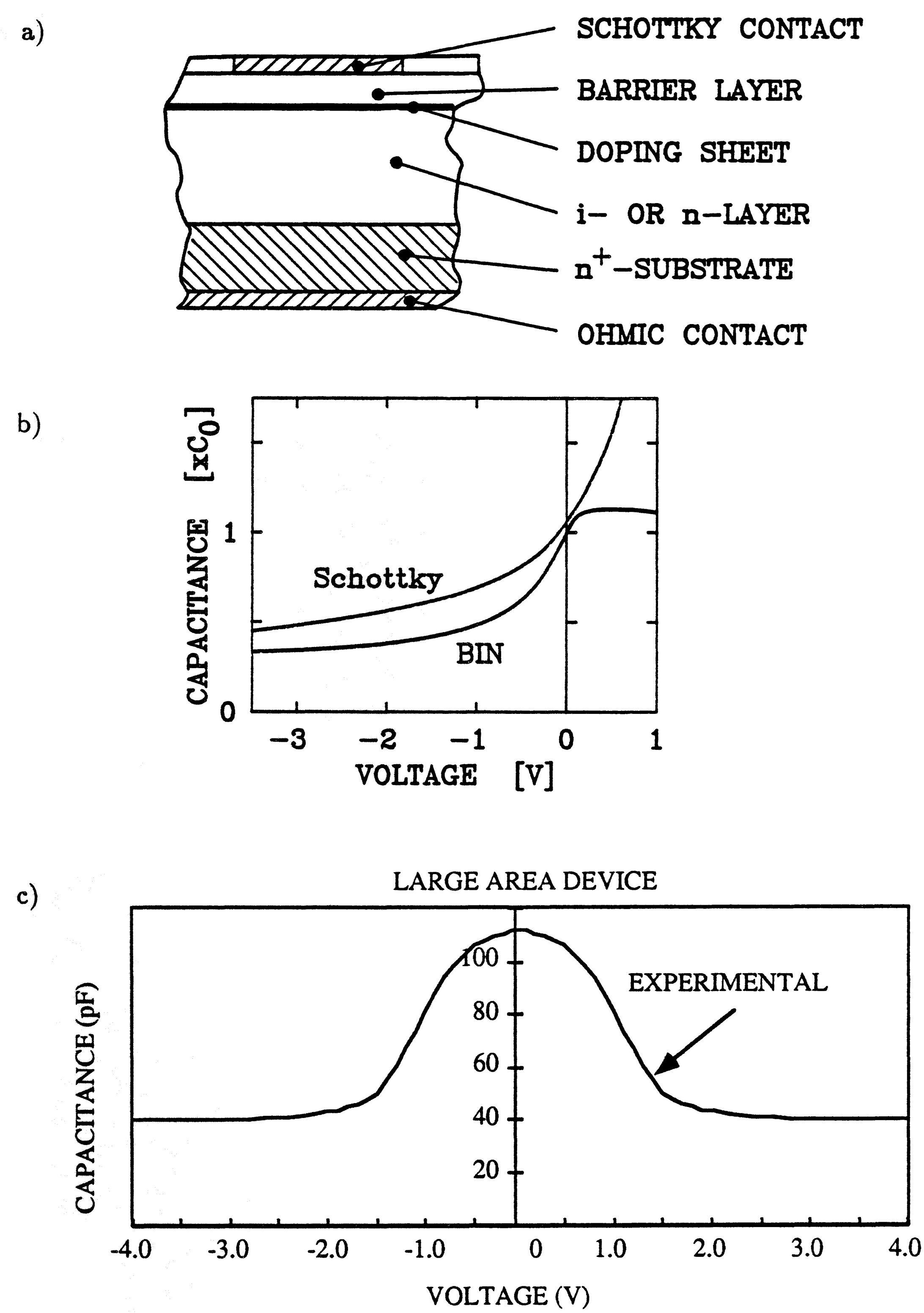

Figure 2. Structure of a single BIN or BNN diode a) its C-V characteristic compared to the C-V curve of a conventional Schottky b), and an experimental C-V characteristic of a large area back-to-back BNN diode c).

a)

b)

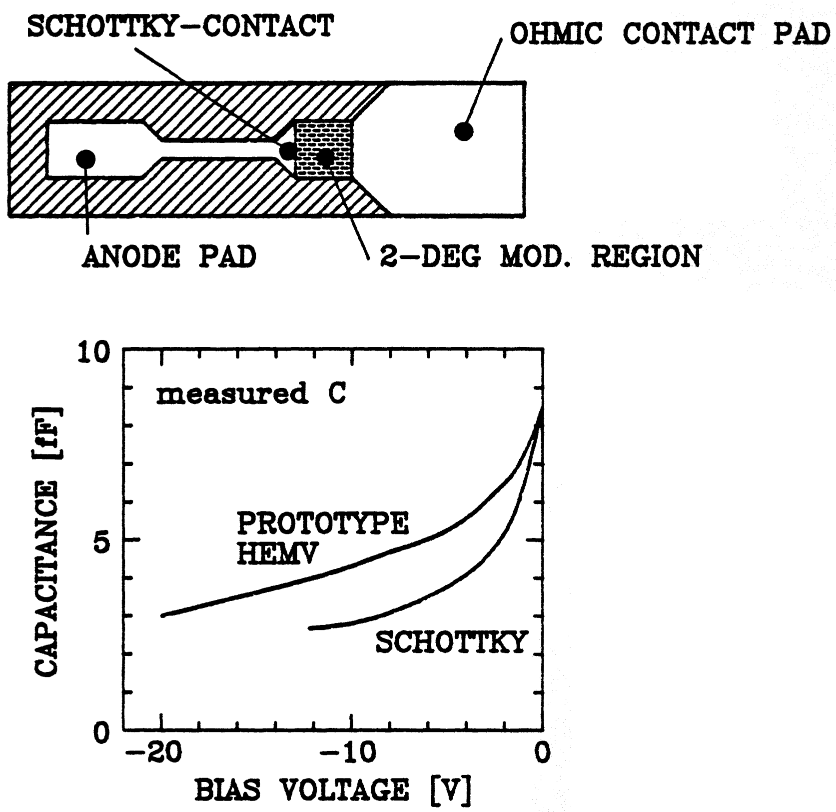

Figure 3. Structure of the high electron mobility varactor a) and its C-V characteristic b).

The equivalent circuit of each diode described above is similar to that of the Schottky varactor. It consists of a parallel combination of a voltage-dependent capacitance and conductance, in series with a frequency (and voltage) dependent resistance. For the present work the simulations were carried out using this diode model and a modified version of the large signal analysis program by Siegel and Kerr [13].

Multipliers for 200 GHz

For diodes having an asymmetric C-V curve, the basic multiplier configuration is a doubler. Fig. 4 illustrates the theoretical efficiency of a delta-doped varactor or BNN and three Schottky varactor (6P2 and 5M2 by University of Virginia and VD011 by Farran Technology) doublers for 200 GHz. Although the nominal diode parameters (Table I) are rather different, the dynamic cut-off frequency is almost equal, which results in the same peak-efficiency. This peak is reached with a voltage swing from near forward conduction

Table I. Parameters used in the analyses of multipliers for 200 GHz. Parameter K is $2\epsilon/qN_dw^2$, see Eq. (1).

200 GHz multipliers				
VD011	$C_0 = 12$ fF, $\gamma_0 = 0.45$,	$R_s = 12\ \Omega$,	$V_{BR} = -15$ V,	$f_{cd} = 3.0$ THz
6P2	$C_0 = 21$ fF, $\gamma_0 = 0.45$,	$R_s = 9\ \Omega$,	$V_{BR} = -20$ V,	$f_{cd} = 2.7$ THz
5M2	$C_0 = 21$ fF, $\gamma_0 = 0.50$,	$R_s = 10\ \Omega$,	$V_{BR} = -15$ V,	$f_{cd} = 2.8$ THz
SBV	$C_0 = 50$ fF, $K = 18\ V^{-1}$,	$R_s = 15\ \Omega$,	$V_{BR} \approx \pm 10$ V,	$f_{cd} = 2.3$ THz
BNN	$C_{max}/C_{min} = 17/5$ fF,	$R_s = 9\ \Omega$,	$V_{BR} = -8$ V,	$f_{cd} = 2.5$ THz
bbBIN	$C_{max}/C_{min} = 18/5$ fF,	$R_s = 24\ \Omega$,	$V_{BR} \approx \pm 7$ V,	$f_{cd} = 1.0$ THz
bbBNN	$C_{max}/C_{min} = 15/5$ fF,	$R_s = 15\ \Omega$,	$V_{BR} \approx \pm 7$ V,	$f_{cd} = 1.4$ THz

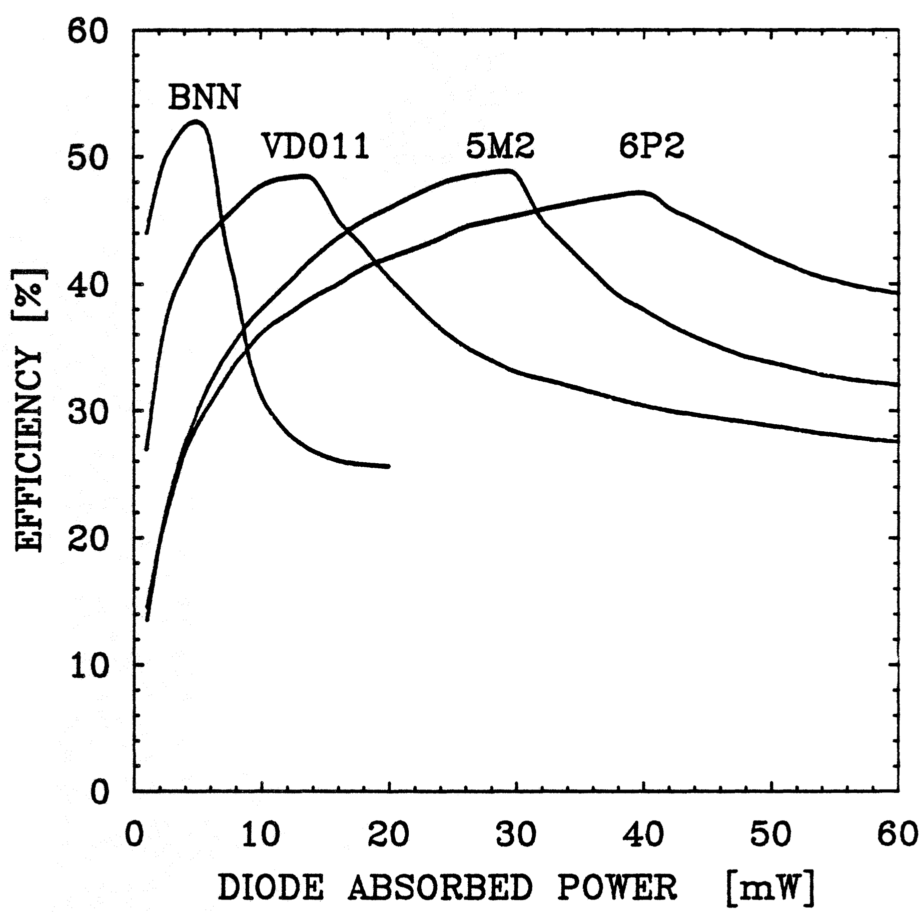

Figure 4. Theoretical efficiency of frequency doublers for 200 GHz. Simulations are based on measured (DC) nonlinearities of the devices.

to the break-down. These diodes can handle more input power, but due to the forward conduction, multiplication then becomes partly resistive which results in a decrease in efficiency. For diode absorbed power, below the peak, the efficiency is determined by the strength of the non-linearity. Hence, the BNN or delta-doped varactor results in excellent performance if the input power level is relatively low.

In general the input power level for peak efficiency is a function of the zero-bias capacitance of a diode. For example, a Schottky varactor having a small area and hence a small C_0 is favorable for applications where input power is limited. Small capacitance results in high input impedance and hence larger voltage swing across the diode for a given input power. Therefore, the break-down voltage limit is reached with rather small input power levels. When higher input power levels are available, a larger capacitance is a better choice, especially if the nonlinearity is sharper (5M2) or break-down limit is higher (6P2).

The prototype high electron mobility varactors had a C-V characteristic which was

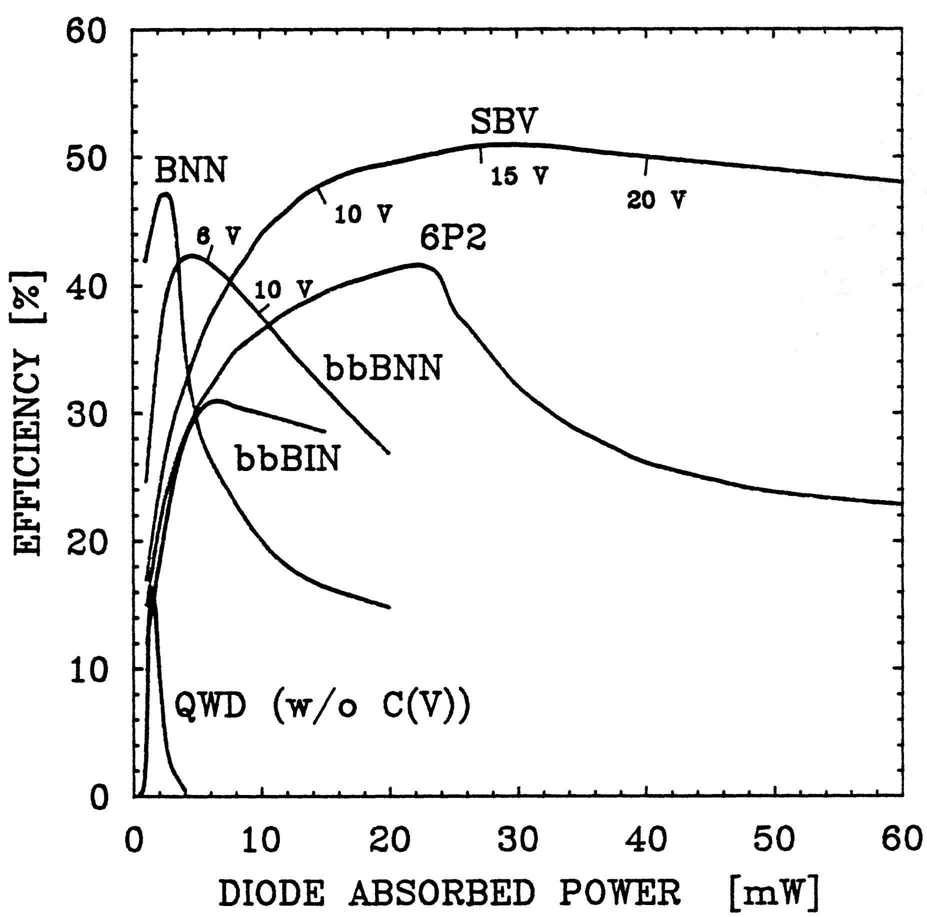

Figure 5. Theoretical efficiency of frequency triplers for 200 GHz.

slightly less nonlinear than that of the conventional Schottky varactor [7]. This was partly due to rather large parasitic capacitance related to the structure. However, it is expected that a reduction of this parasitic capacitance will result in a curve which is as steep as that of the conventional Schottky [14]. This together with a measured high break-down voltage [7] make this device very attràctive especially for applications, where the input power level is high.

Comparison of triplers to 200 GHz is shown in Fig. 5. Below the peak, where the multiplication is purely reactive, the theoretical tripling efficiency of the 6P2 and the BNN or delta-doped varactor is close to their doubling efficiency. This is because the input impedance of a tripler for 200 GHz is higher than the impedance of a doubler for the same output frequency, causing more efficient capacitance modulation. This partly "compensates" additional losses in the diode series resistance at the idler frequency. However, because a good idler termination is crucial for the operation of both devices, degradation of efficiency will be more severe in practice, due to the difficulty of arranging separate tuning for each harmonic.

The need for an idler can be avoided using a device having a symmetric C-V curve, such as a single barrier varactor (SBV) or back-to-back BNN (bbBNN). If there is no current leakage through the single barrier varactor, its highly nonlinear C-V curve together with a high dynamic cut-off frequency, results in an excellent 3rd harmonic generation without the need of an idler. As a hypothetical extreme, a similar size ($\approx$4-μm-diam.) quantum well diode (QWD) was analyzed assuming that multiplication is purely resistive (Experimentally, the voltage variable capacitance dominates the multiplication). The dramatic difference between resistive and reactive multiplication can be seen in Fig. 5. Despite the highly nonlinear I-V curve of the quantum well diode, its theoretical performance for varistor operation is much less than the varactor's performance.

The back-to-back BIN (bbBIN), also has a sharp symmetric C-V curve, but its rather low dynamic cut-off frequency decreases the conversion efficiency. A doped version, a back-to-back BNN, has a lower series resistance and therefore higher cut-off frequency. This results in better performance at moderate pump power. Doping in the epitaxial layer degrades the sharpness of the C-V curve so that the efficiency at low pump power is reduced.

Experimentally, the efficiencies available from multipliers will be lower due to resistive losses, which in the 200-GHz range in a well-made waveguide mount are typically around 1.5–2 dB, with an additional 0.5–1 dB for each idler frequency. The efficiency will further decrease due to the difficulty to provide the device with optimum terminations at each harmonic frequency. For the best performance, the diode should be matched at the input

Table II. Parameters used in the analysis of the multipliers for 1000 GHz.

1 THz multipliers					
2T2	$C_0 = 5.5$ fF,	$\gamma_0 = 0.45$,	$R_s = 12\ \Omega$,	$V_{BR} = -10$ V,	$f_{cd} = 5.8$ THz
SBV	$C_0 = 15$ fF,	$K = 18\ \text{V}^{-1}$,	$R_s = 20\ \Omega$,	$V_{BR} \approx \pm 10$ V,	$f_{cd} = 5.0$ THz
QWD(C)	$C_0 = 50$ fF,	$K = 112\ \text{V}^{-1}$,	$R_s = 20\ \Omega$,	$V_{BR} \approx \pm 3$ V	
BNN	C_{max}/C_{min}	$= 4.5/1.2$ fF,	$R_s = 17\ \Omega$,	$V_{BR} = -8$ V,	$f_{cd} = 5.7$ THz
bbBIN	C_{max}/C_{min}	$= 7.5/2.1$ fF,	$R_s = 40\ \Omega$,	$V_{BR} \approx \pm 5$ V,	$f_{cd} = 1.4$ THz
bbBNN	C_{max}/C_{min}	$= 5.6/2.0$ fF,	$R_s = 20\ \Omega$,	$V_{BR} \approx \pm 5$ V,	$f_{cd} = 2.6$ THz

and output frequency, and terminated at the idler(s) with an inductance which resonates with the average capacitance at that particular frequency. At harmonic frequencies higher than the output an optimum termination is an open circuit, because other terminations

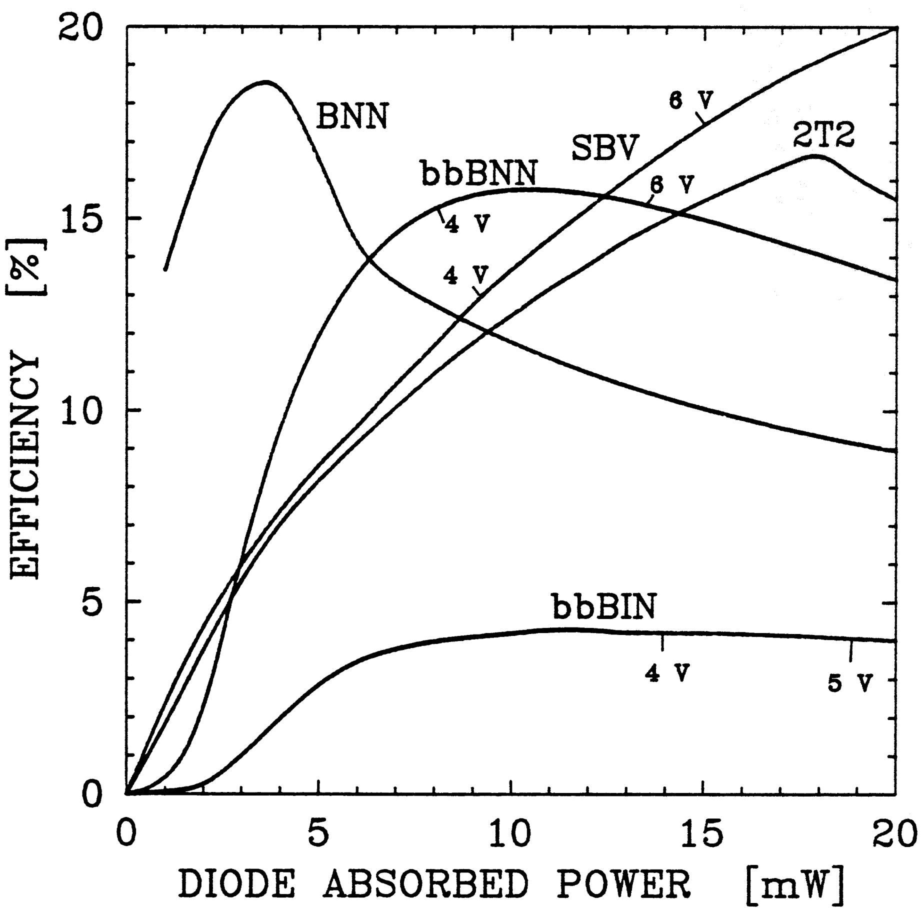

Figure 6. Theoretical efficiency of frequency triplers for 1000 GHz.

(worst case is an inductance which resonates the capacitance) allow current flow which generally introduces extra losses in the diode series resistance.

Multipliers for 1000 GHz

Accurate analyses of multipliers for 1 THz are more complicated due to various effects which become more important at high frequencies, or when the order of multiplication increases. These effects include current saturation and the limited speed of the edge of the depletion region. In the following analyses, the basic equivalent circuit is used and the emphasis is based on the nonlinearities of the devices. This will give an optimistic upper limit for the performance of the devices. A more detailed discussion on the current saturation can be found elsewhere in this proceedings [15].

Fig. 6 illustrates the theoretical efficiency of various devices working as a tripler for 1 THz. The maximum input power available from present solid-state sources at 333 GHz

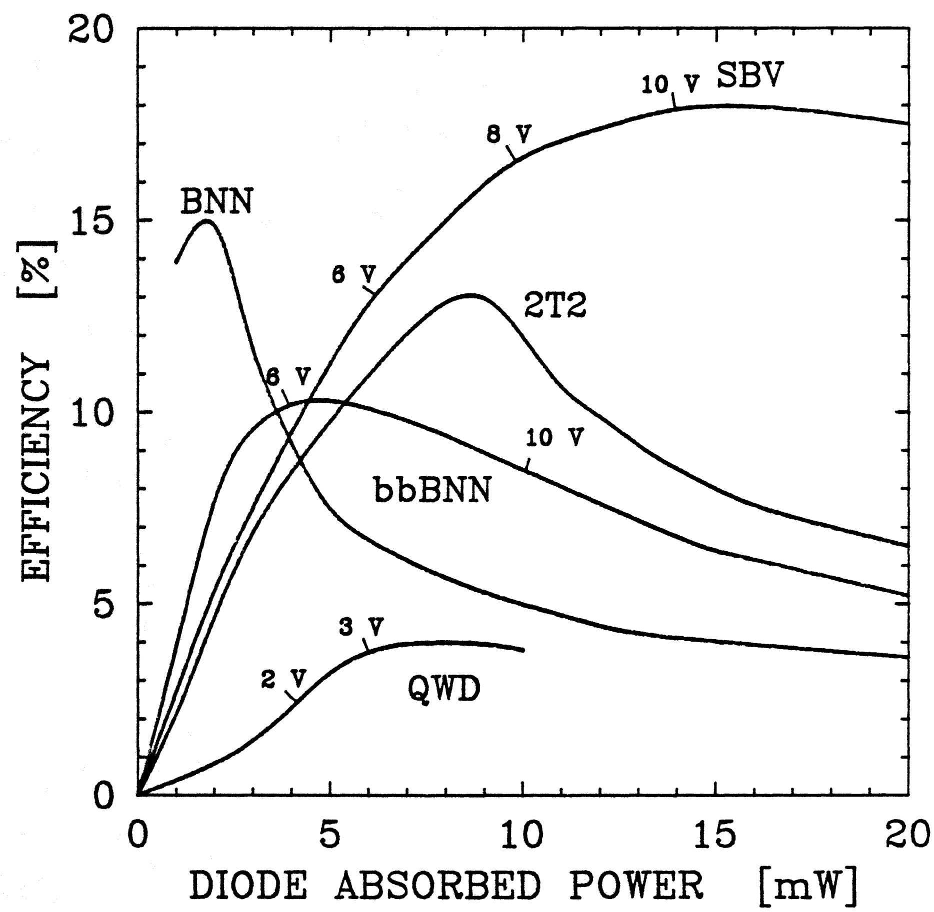

Figure 7. Theoretical efficiency of frequency quintuplers for 1000 GHz.

is below 5 mW. At this pump power, the BNN or delta-doped varactor will be superior, exceeding the efficiency of the 2T2 (U.Va) and the single barrier varactor by a factor of three. Also, the back-to-back BNN configuration works very well, and has an additonal advantage that no idlers are needed. Similarly, Fig. 7 illustrates the theoretical efficiency of various quintuplers for 1 THz. In this case, the maximum input power level available from solid-state sources at 200-GHz input range is around 10–20 mW, which makes the single barrier varactor the most attractive device. In the quintupler case, it should also be remembered that devices having asymmetric curves (BNN and standard Schottky) require three idler terminations for the performance shown in Fig. 7. The 2nd harmonic idler termination is essential, but idlers at the 3rd and 4th harmonics are "alternative". However, the theoretical efficiency of a Schottky varactor, for instance, decreases at least by a factor of two if either of these is missing. Devices having symmetric curves require only one idler termination (which is essential) at the 3rd harmonic frequency. Therefore, the symmetric devices will suffer less from unoptimized idler terminations.

Conclusions

The GaAs Schottky varactor has long been the only efficient component for millimeter and submillimeter wave frequency conversion. However, during the past few years growing interest in novel structures and semiconductor materials have brought to light several new devices which utilize a stronger nonlinearity or a special-symmetry in their characteristics.

The sharp C-V dependence of the barrier-n-n$^+$ diode (delta-doped varactor) improves performance at low input power levels, making it very attractive in the submillimeter wave regime. The highly nonlinear, symmetric C-V curve of the single barrier varactor yields excellent performance theoretically, whereas the antisymmetric I-V curve of the quantum well diode, since it suffers resistive losses, is less efficient. The structure of back-to-back BIN/BNN diodes and the high electron mobility varactor is inherently planar which yields higher reliability, especially for space-borne applications.

In conclusion, these novel devices have some benefits which make them attractive in specific applications, especially at submillimeter wavelengths. In the near term, the conventional Schottky varactor will continue to be the device of choice for most applications. However, all of the novel diodes are considerably less mature than the Schottky varactor. Therefore, there should be a great opportunity for future device optimization.

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