# Consideration of Velocity Saturation in the Design of GaAs Varactor Diodes

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*Abstract*—**The design of GaAs Schottky barrier varactor diodes is reconsidered in light of the recent discovery of velocity saturation effects in these devices. Experimental data is presented which confirms that improved multiplier performance can be achieved.**

## I. Introduction

GaAs SCHOTTKY varactor diodes are commonly used to multiply the output of Gunn diodes to higher frequencies for use as local oscillator power for heterodyne receivers [1], [2]. These all-solid-state sources are quite reliable, compact, relatively inexpensive, and have been space qualified. Although many new types of varactor devices have been proposed in recent years, they have not yet demonstrated substantial benefits over the standard GaAs Schottky diode.

A whisker contacted Schottky diode is sketched in Fig. 1. The primary design parameters are the epitaxial layer doping density, the anode diameter and the thickness of the epitaxial layer. The device characteristics that can be adjusted by varying these parameters are the junction capacitance, the series resistance and the breakdown voltage. The junction capacitance is given as [3]

$$C_j = \frac{\epsilon A}{X_d} + \frac{3\epsilon A}{d}, \quad (1)$$

where $\epsilon$ is the dielectric permittivity of GaAs, $A$ is the Schottky area, and the depletion depth, $X_d$, is voltage-variable and approximated as

$$X_d = \sqrt{\frac{2\epsilon}{qN_d}(V_{bi} + V_R)}, \quad (2)$$

where $q$ is the electronic charge, $V_{bi}$ is the built-in potential of the barrier, and $V_R$ is the applied reverse voltage. The anode diameter, $d$, and epitaxial layer doping density, $N_d$, are typically chosen to achieve a good impedance match in the multiplier circuit at both the input and output frequencies.

It is the voltage dependence of the junction capacitance that is used to achieve frequency multiplication. A diode with a lower doped and thicker epitaxial layer will generally have a larger reverse breakdown voltage and thus greater possible capacitance modulation. This leads to greater multiplier efficiency and power handling ability.

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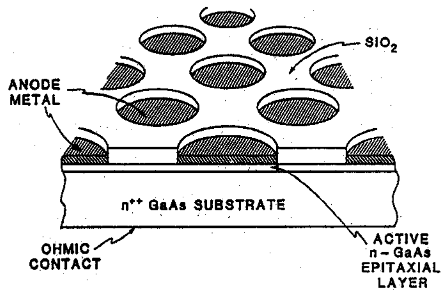


Fig. 1. A cross-sectional sketch of a typical GaAs Schottky varactor diode.

The diode series resistance is due to the impedance of the substrate and the undepleted epitaxial layer. To reduce the substrate's series resistance, its doping density is made as high as possible. The undepleted epitaxial layer is the primary source of series resistance, and thus it would seem to be beneficial to increase its doping density and make it thinner. However, this reduces the breakdown voltage, thereby limiting the diode's capacitance modulation and power handling ability. Clearly a trade-off exists. Since the goal in developing millimeter wavelength multipliers is often to achieve the highest possible output power, it has been common to use an epitaxial layer that is low in doping and quite thick. For example, the 6P4[1] type varactor has a doping density of $3.5 \times 10^{16}\text{cm}^{-3}$ and a thickness of about $1\mu$m (Table I). This diode has been extremely successful at millimeter wavelengths and has been used by a variety of researchers [1], [2], [4]. However, it will be shown in the following sections that the design of the 6P4 diode is not optimal.

## II. Velocity Saturation Effects

The importance of velocity saturation in high-frequency varactor diodes was first pointed out by Kollberg in 1991 [5], and a detailed discussion of these effects is presented in [6]. For the purposes of this letter, a simplistic description of how velocity saturation can affect varactor diode performance is sufficient. Consider the 6P4 diode as a varactor with a pump frequency of 100 GHz. The pump power causes the voltage applied to the diode to vary, causing the depletion region

[1] The 6P4 is identical in design to the earlier diodes 6P1 and 6P2, which are referred to in many previous publications.

TABLE I
NOMINAL DIODE PARAMETERS

| Diode Batch | Epitaxial Doping Density ($cm^{-3}$) | Epitaxial Thickness ($\mu$m) | Anode Diameter ($\mu$m) | Series Resistance ($\Omega$) | Breakdown Voltage (V) | Zero-Bias Capacitance ($fF$) | Capacitance at Breakdown ($fF$) |
|---|---|---|---|---|---|---|---|
| 6P4 | $3.5 \times 10^{16}$ | 1.0 | 6.3 | 9.5 | 20 | 20 | 5 |
| 5T1 | $1 \times 10^{17}$ | 0.6 | 4.7 | 5.3 | 10 | 22 | 7.5 |

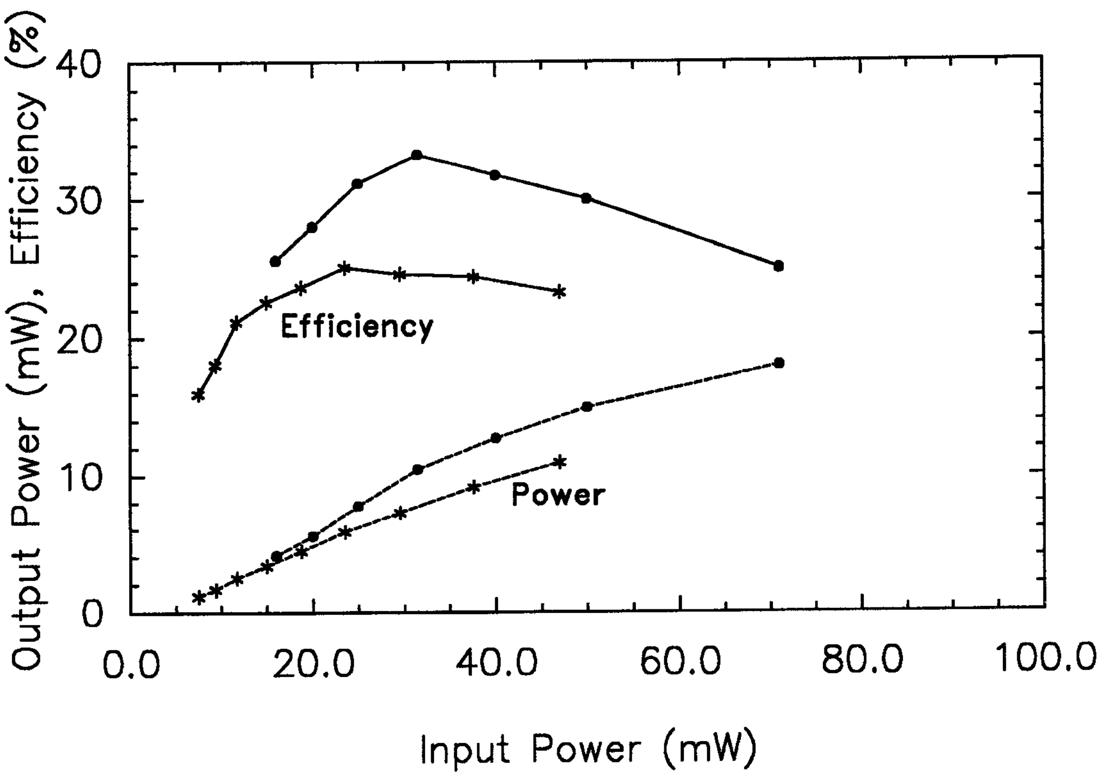


Fig. 2. The efficiency (solid) and output power (dashed) of a 100–200-GHz doubler with 6P4 (*) and 5T1 (•) diodes.

thickness to be modulated. As the power is increased, the amplitude of the depletion region modulation increases. Since the time period for this modulation is constant, the increasing power requires higher electron velocity if the depletion region is to fully track the voltage swing. However, at some power level the electron velocity saturates, and further increases in power do not increase the depletion region (and therefore the capacitance) modulation. At this point the standard models of varactor diode operation, which assume a constant electron mobility, fail. Furthermore, as the input frequency is increased, the power level at which velocity saturation occurs decreases.

The 6P4 diode is a very successful varactor element in doublers from 100–200 GHz. However, its experimental performance has never approached the predictions of standard multiplier analysis [7,6]. Kollberg has explained this problem by pointing out that (at 80 GHz) the average electron velocity assumed by the multiplier analysis program reaches a value in excess of the actual saturation velocity at an input power level of only 11 mW, while these diodes are typically driven by power levels up to 50-60 mW [5,6]. Thus, the analysis must be extended to include velocity saturation effects if it is to accurately predict the multiplier performance.

## III. AN IMPROVED VARACTOR DIODE DESIGN

To our knowledge, velocity saturation has not yet been incorporated into any multiplier analysis program. Thus, the varactor diodes cannot yet be precisely optimized. However, the assumption that the entire epitaxial layer of the 6P4 diode is utilized is clearly not true. Since any extra epitaxial material adds series resistance, a reduced epitaxial layer thickness may improve varactor performance.

To test this hypothesis, we have fabricated a new device (5T1) with a substantially thinner epitaxial layer. Also, since the layer is thinner, its doping density was increased approximately to the point where reverse breakdown occurs as the (thinner) epitaxial layer is depleted. This was done to further reduce the series resistance without degrading the capacitance modulation. Parameters for the 6P4 and 5T1 diodes are given in Table I. The anode diameter of the 5T1 was chosen so that both diodes would have roughly the same zero-bias capacitance and could therefore be tested in the same multiplier mount. The new diode has roughly half the breakdown voltage of the 6P4, and thus a reduced capacitance modulation (measured at dc). However, the new design yields nearly a factor of two decrease in series resistance. Since we believe that the dc measured capacitance modulation of the 6P4 is not actually achieved at millimeter wavelength, the 5T1 should be the better design.

## IV. Experimental Results and Discussion

The 5T1 diode was tested in a doubler from 100 GHz to 200 GHz. The multiplier block was an existing design that has been previously described [1] and has been used for many years with the 6P4-type diodes. The measured efficiency and output power are graphed as a function of input power in Fig. 2. The peak efficiency was about 33% at an input power level of 31.5 mW. The results for a good 6P4 diode are also presented in the graph. The new diode has greater efficiency than the 6P4 at all power levels and the peak efficiency is achieved at a higher power level. This indicates that the reduced epitaxial layer thickness has not reduced the capacitance modulation of the diode at the pump frequency. This is an important indication that the velocity saturation effects are indeed degrading the performance of the standard varactor.

## V. Conclusion

We have redesigned a GaAs Schottky barrier varactor diode for millimeter wavelength applications by taking into account velocity saturation effects. The new design uses a thinner epitaxial layer and a higher epitaxial layer doping density. Although this reduces the breakdown voltage, and therefore the capacitance modulation measured at dc, the actual capacitance modulation at the pump frequency does not appear to be significantly degraded. Also, the new design leads to substantially reduced series resistance. The new diode has yielded significantly better performance than the best previous device in a 100–200-GHz doubler, with peak efficiency of 33% at 31.5-mW input. This result is experimental confirmation of the importance of velocity saturation effects in millimeter wavelength varactor diodes.

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