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2-D Design of Schottky Diodes

Jesús Grajal, Daniel Moreno and Viktor Krozer

Abstract— **The optimization of Schottky diode operation together with the design of circuits based on these devices can be accomplished with a developed 2-D drift-diffusion simulator. Evaluation of the impact of different geometries on the device performance and study of limiting processes like velocity saturation at high frequencies are analysed with this simulation tool.**

I. Introduction

GaAs Schottky barrier diodes continue being the key elements for mixers (heterodyne receivers) and frequency multipliers (all-solid-state power sources) for millimeter and sub-millimeter bands. The key points in the progress of the performance of circuits based on Schottky diodes have been the enhanced physical insight into and the optimization of submm-wave Schottky diode operation [1], the improvement in frequency multiplier and mixer analysis methods, and in physical analytical Schottky diode models [2], [3], as well as numerical physical device models [4]. The last milestone in this progress is the coupling of numerical physical models and circuit simulators which enables the co-design of circuits and devices [4], [5]. These advanced tools can only be effective with accurate physical models which allow the analysis of different structures without empirical adjustment parameters. Furthermore, these models must account for the limiting mechanisms at high frequency and high power operation. Besides, these simulators must be able to evaluate the impact of different geometries on the device performance. This is not possible using an *1-D* simulator developed in the past [5].

We have developed a *2-D* numerical simulator based on the drift-diffusion theory which incorporates the accurate physical model considered in the *1-D* numerical simulator: impact-ionization, non-constant recombination velocity, self-consistent incorporation of the tunnelling and image-force effects. The geometrical aspects are included by the two-dimensional nature of the simulations. Figure 1 shows the different structures (half of the device exploiting axial or plane symmetry) which can be analysed with this simulator. It is also clear that it is possible to study planar diodes with the ohmic contact at the top of the device (ohmic contact identified with symbol (0), figure 1), and Whisker and quasi-vertical planar diodes with the ohmic contact at the rear (ohmic contact identified with symbol (1), figure 1).

This simulator was validated by comparison of simulated device characteristics with experimental results obtained for submm-wave Schottky diodes fabricated at the University of Darmstadt (*TUD*). After this initial step, we focused on the impact of different geometries on the device electrical characteristics and also on the study of some limiting physical processes at high frequencies like velocity saturation. The objective of this paper is to show that this simulator is an appropriate tool for both the study of physical properties of these devices and the design of real devices.

Jesús Grajal and Daniel Moreno are with the ETSIT, Universidad Politecnica Madrid, Ciudad Universitaria s/n, 28040 Madrid, Spain, email:jesus@gmr.ssr.upm.es

Viktor Krozer is with the Lehrstuhl für Hochfrequenztechnik, TU Chemnitz, Reichenhainerstr. 70, D-09126 Chemnitz, Germany, email: vkrozer@infotech.tu-chemnitz.de

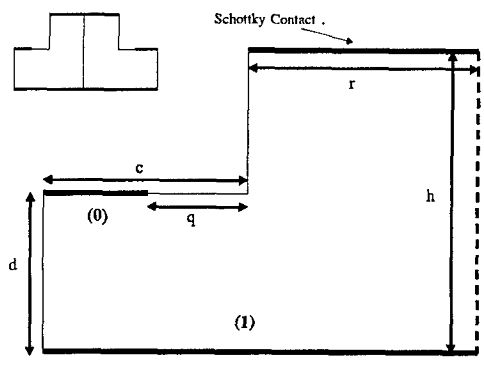


Fig. 1. Possible geometries in the *2D* simulator. (*i*) identifies the position of the ohmic contacts.

TABLE I

Parameters for Schottky diodes from TUD and UVa.

Diode	Epitaxial Layer		$V_{bd,DC}$ (V)
	doping (cm^{-3})	length (μm)	
D1038	3×10^{17}	0.560	−8
UVa 6P4	3.5×10^{16}	1.0	−20
D1038	subs. doping: $2 \times 10^{18} cm^{-3}$ length: 80-100 μm		

II. Geometrical aspect of the design of Schottky diodes

Impact of the geometry on the series resistance R_s and the capacitance C of Schottky diodes can be directly studied with this simulator. These parameters are important because their optimization can improve the frequency performance of these devices, which is often measured by the cut-off frecuency: $f_{c0} = \frac{1}{2\pi R_s C_{j0}}$, where $C_{j0} = C(V_{bias} = 0)$.

Figure 2 shows the series resistance of a cylindrical Schottky diode, *D1038*, whose doping profile is described in table I. The ohmic contact is at the rear of the device and the radius of the Schottky contact is $r_{SC} = 5\ \mu m$ ($\phi = 2 \cdot r_{SC}$ in figure 1) for different substrate lengths and radii of the ohmic contact ($r_{ohmic} = c + r_{SC}$ in figure 1). It is important to notice that the distribution of the current in the substrate changes depending on the relationship between h ($h \approx L_{substrate}$) and r_{ohmic} (figure 1), and this is the origin in variations of the series resistance. For short substrates the resistance does not depend on the radius of the ohmic contact. We have also concluded that the resistance does not depend on the size of ohmic contact, regardless the length of the substrate for $c \geq (3-4) \cdot r_{SC}$. Similar results apply for for another Schottky diode with $r_{SC} = 2.5$ μm as can be observed in figure 3.

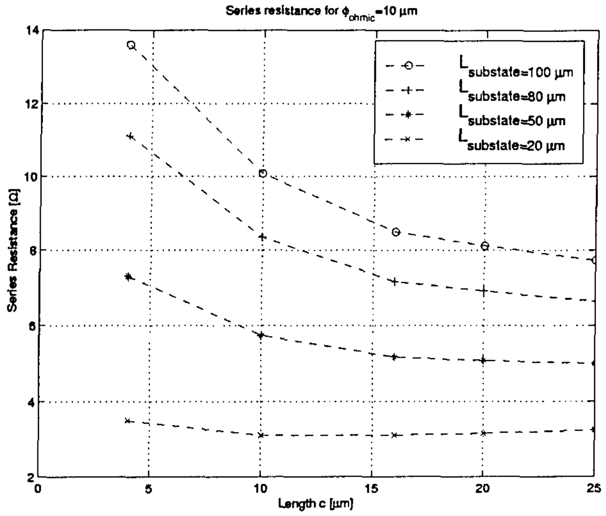


Fig. 2. Series resistance vs. radius for the ohmic contact for different substrate lenghts. The ohmic contact is at the rear of the device and radius of the Schottky contact is $r_{SC} = \frac{\phi}{2} = 5$ μm.

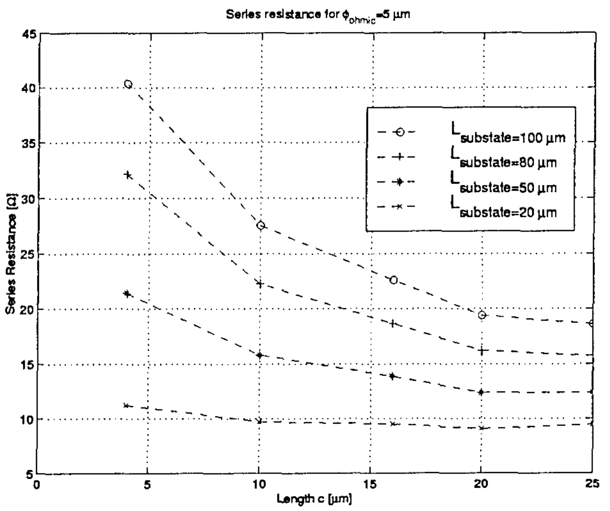


Fig. 3. Series resistance vs. radius for the ohmic contact for different substrate lenghts. The ohmic contact is at the rear of the device and radius of the Schottky contact is $r_{SC} = \frac{\phi}{2} = 2.5$ μm.

A similar study has been performed for this device with the ohmic contact at the top for different substrate lenghts and distances between the contacts: $c - 3$ μm, as can be seen figure 4. For this structure, the series resistance decreases for increasing substrate lengths because the area for the current flux increases. The differences among the analysed structures are nearly negligible for distances between contacts less than 5 μm.

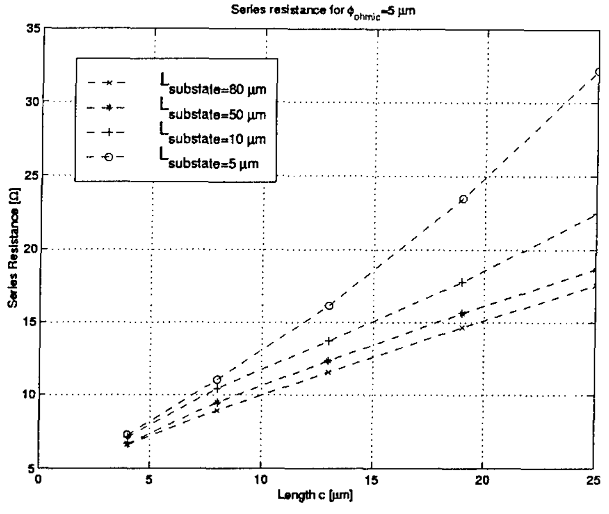


Fig. 4. Series resistance vs. distance between contacts ($c - 3$ μm, figure 1) for different substrate lenghts. The ohmic contact is at the top of the device with radius $r_{ohmic} = 3$ μm. The radius of the Schottky contact is $r_{SC} = \frac{\phi}{2} = 2.5$ μm.

The capacitance of a small-area submillimeter-wave diode is strongly affected by the edge effects as has been pointed out by several researchers [6]. Figure 5 presents the correction factor γ_C for the capacitance due to edge effects [6] as a function of the radius of the anode for several doping densities in the epitaxial layer. It is clear that the edge effect only impacts on the characteristics of the device if the radius is small enough compared to the length of the epitaxial layer W_{epi} ($\frac{r_{SC}}{W_{epi}} < 3-4$), which is typical for submillimeter varactors. Of course, the influence of the edge effects also depends on the doping density of the diode as can be observed in figure 5.

The accurate calculation of the capacitance is fundamental for the design of varactors working as frequency multipliers, where the basic non-linearity for generating harmonics is the capacitance. Besides, the design of the device geometry in order to reduce the series resistance will impact dramatically on the efficiency of a multiplier.

III. High frequency limiting mechanisms: Velocity saturation

Besides geometrical aspects, a numerical simulator is also a useful tool to gain physical insight into the diode operation. High frequency operation of Schottky diodes working as frequency multipliers or mixers is limited by the velocity saturation effect [1]. It has been outlined in [7] that the current saturation mechanism should not occur for well designed diodes at all operating frequencies. This can be achieved by choosing a sufficiently high doping density in the device $N_D \geq J_{disp}/qv_{max}$ with J_{disp} being the displacement current and v_{max} the maximum velocity of electrons in the epi-layer region outside the space charge region. Ho-

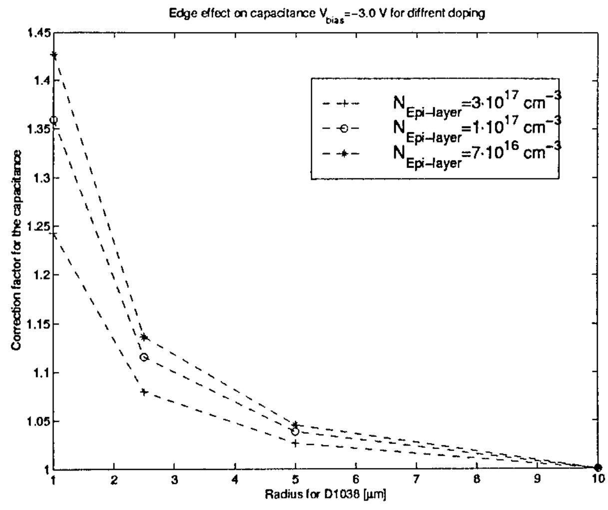


Fig. 5. Correction factor γ_c [6] for several anode radii and doping densities. Other parameters for this diode are from table I D1038. The ohmic contact is at the rear of the device with a radius of $r_{SC} + 4\ \mu m$.

wever, this has an adverse effect on the breakdown voltage. The impact of saturation velocity on the performance of diode $UVa - 6P4$ from the University of Virginia, table I, has been demonstrated in [4] at a fundamental frequency of 100 GHz. This diode suffers from velocity saturation at this frequency because of its low doping concentration in the epi-layer.

This effect is also observed in highly doped devices at higher frequencies as illustrated in figure 6, where the edge of the depletion region can follow the voltage waveform at $100\,GHz$, but cannot follow the RF voltage waveform at $700\,GHz$. The diode contact is at right-hand side in figure 6. The diode is similar to *D1038* with $R_{SC} = 2.5\ \mu m$, but with different epi-layer doping This point can be better observed in figure 7 through contours of the space charge region edge for $100\,GHz$ and $700\,GHz$. The velocity saturation effect produces a smaller modulation of the space-charge region during one period of the exciting signal, which in turn leads to a smaller capacitance modulation, with the corresponding decrease in the efficiency in frequency multipliers. Therefore, a maximum frequency for the pump signal can be defined at which velocity saturation effects become important. It is also interesting to point out that the modulation of the space charge region has hysteretic behaviour under high frequency pumping [8].

Figure 8 presents the maximum pump frequency versus doping concentration calculated with the analytical model presented in [7] and with the numerical model introduced here. The analytical model is based on simple equations for depletion layer depth, critical electric field, and the avalanche breakdown voltage (the voltage swing is selected such that it sweeps from the breakdown to forward conduction $V_{RF} = (V_D - V_{bd;DC})$). In the numerical model, the calculated maximum pump frequency is defined as the frequency where the amplitude of the calculated current is 25 % less than the extrapolated amplitude for lower frequencies. Given a doping concentration of $N_{epi} = 2 \cdot 10^{17}/cm^3$ the maximum pump frequency without velocity saturation effects is found to be $f_c \leq 210 GHz$.

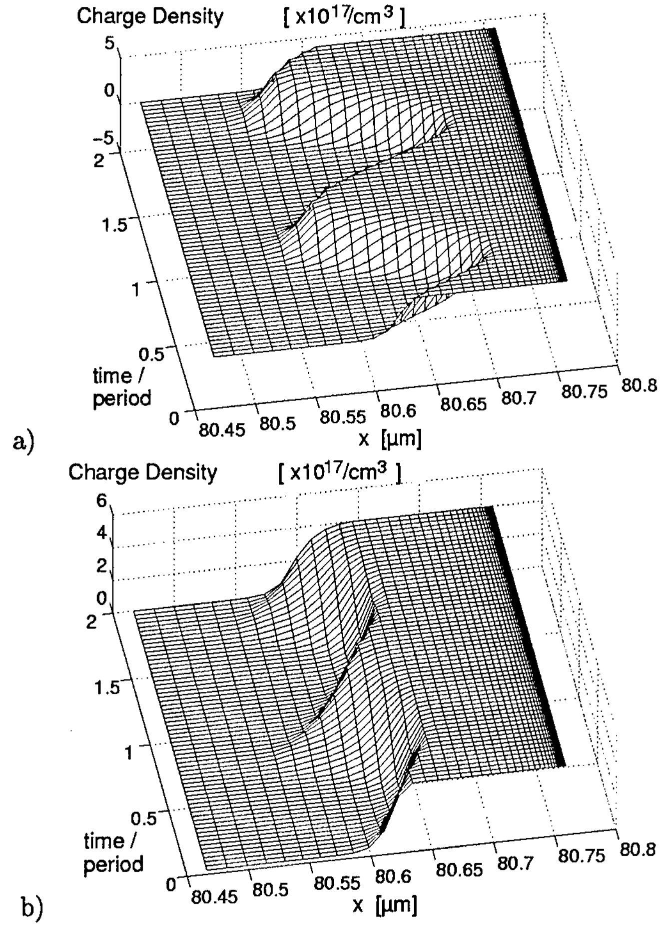
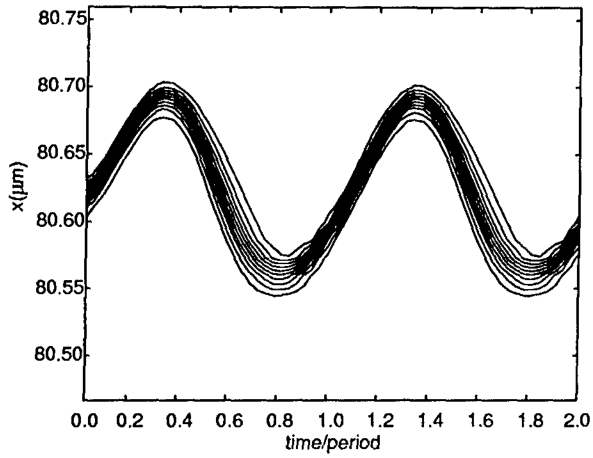


Fig. 6. Variation of the edge of the depletion region with applied RF voltage at a) signal frequency of $100\,GHz$, b) signal frequency of $700\,GHz$. The epi-layer doping is $N_{epi} = 4 \cdot 10^{17}/cm^3$, the epi-layer thickness is $t_{epi} = 560\ nm$, and the substrate length is 80 μm (the Schottky contact is on the right-hand side).

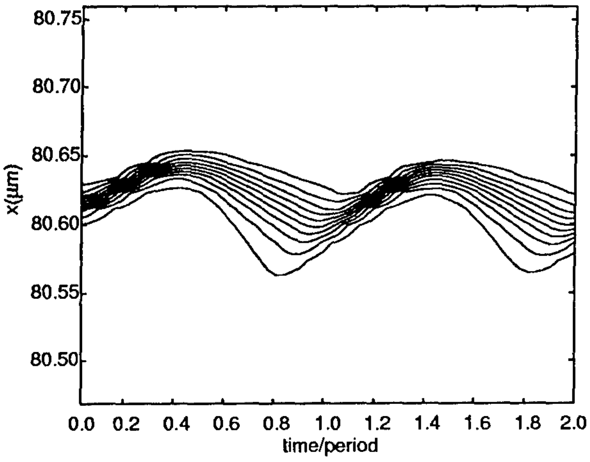
It is possible to increase the maximum pump frequency by decreasing the magnitude of the bias voltage. For a given doping concentration, the maximum pump frequency can be varied by changing the bias voltage and the RF voltage swing as can be demonstrated in figure 9 both for the analytical and numerical method. This implies that velocity saturation effects can be avoided by decreasing the bias voltage for a given doping concentration.

IV. Conclusions

Two-dimensional simulator is a helpful tool for the design and optimization of Schottky diodes both from the geometrical point of view and from physical considerations. The two-dimensional simulator allows to minimize parasitics like series resistance by a proper design of the geometry. Besides, a more accurate computation of the capacitance taking into account edge effects will result in a more accurate design of frequency multipliers.



a)



b)

Fig. 7. Time waveforms of the depletion region edge corresponding to figure 6 a) signal frequency of $100\,GHz$, and b) signal frequency of $700\,GHz$.

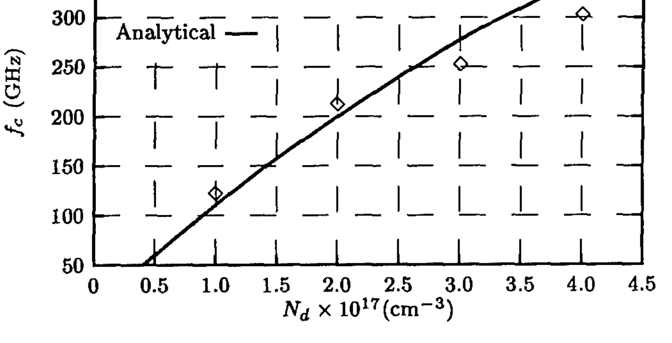


Fig. 8. Maximum pump frequency versus epi-layer doping concentration for optimum operation.

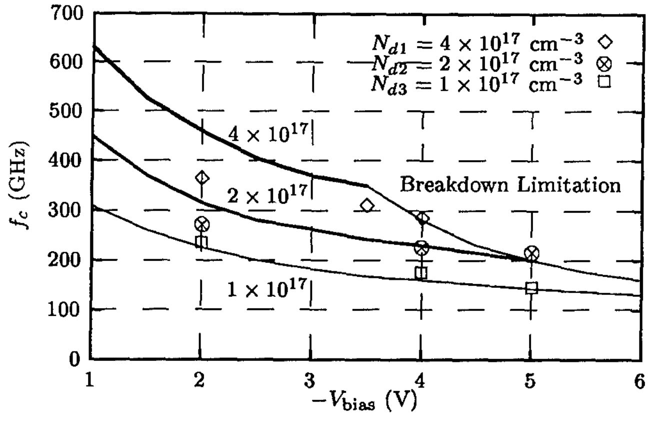


Fig. 9. Maximum pump frequency versus bias voltage V_{bias} for three different doping profiles. The RF swing is chosen as $V_{RF} = 2 \times (V_D - V_{bias})$. The continuous lines are analytical results from [7].

The limiting mechanisms for high frequency operation of Schottky diodes have been discussed. It has been demonstrated that saturation velocity effects could be omitted for well designed diodes at all operating conditions.

Acknowledgments

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