On the Modelling of the Millimeter Wave Schottky Varactor

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Abstract

Schottky varactor frequency multipliers are used to generate the local oscillator power at millimeter and submillimeter wavelengths. The aim of this study is to model the edge effects of the small-area circular anode in order to take them into account in all components of the equivalent circuit. The equivalent circuit contains a junction capacitance, a junction conductance, a series resistance and a model for electron velocity saturation. The correction factors due to the edge effect for the junction capacitance and for the series resistance are available in the literature. In this work we have modelled the electron velocity saturation by limiting the velocity of the transition front between the depleted and undepleted layer. By using this model the maximum current of the diode is given by the actual area of the transition front between depleted and undepleted layers. We have used our new model to analyse the two diode balanced doubler for 160 GHz constructed earlier by Erickson. The agreement between the theoretical results and the measurements is excellent, when the physical parameters of the epitaxial layer and the correction terms due to the edge effects are employed.

1 Introduction

Frequency multipliers are used to generate the all-solid-state local oscillator power of heterodyne receivers at millimeter and submillimeter wavelengths [1]. These local oscillators are needed in many near future scientific satellites (SWAS, Odin, FIRST and SMIM). At millimeter and submillimeter wavelengths a Schottky varactor is the most commonly used multiplier device, although several novel varactors have been proposed [2].

Although the equivalent circuit of the Schottky varactor has been widely studied, varactor fabrication technology has been greatly improved and many different kind of multiplier structures have been tried, the maximum output power of all-solid-state local oscillators remains low at submillimeter wavelengths. The aim of this work is to develop the equivalent circuit of the Schottky varactor in order to find a model, which is physically valid at millimeter and submillimeter wavelengths .

2 Model of Schottky varactor

The Schottky varactor consists of a circular metallic anode on top of a epitaxial GaAs as shown in Figure 1. The radius of the anode is R_0 and the thickness of the epitaxial layer is t_e. At millimeter and submillimeter wavelengths the radius of the varactor anode is not large compared to the thickness of the epitaxial layer and to the width of the depletion layer. Due to the small-area circular anode the potential of the epitaxial layer as well as the transition front between the depleted and undepleted layer are curved near the periphery of the circular anode as shown in Figure 1. This edge effect should be taken into account in the equivalent circuit of the Schottky varactor, which includes

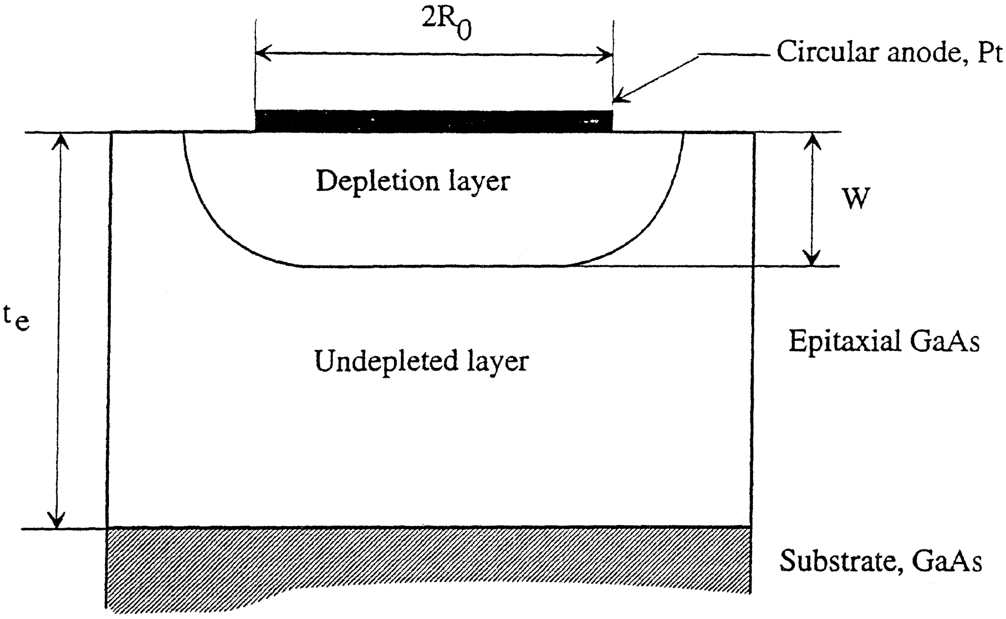

Figure 1: Schematic of a Schottky varactor.

typically a nonlinear junction capacitance, a nonlinear junction conductance and a linear or nonlinear series resistance [1]. At millimeter and submillimeter wavelengths a model of the electron velocity saturation should also be included to the equivalent circuit of the Schottky varactor.

2.1 Junction capacitance

The capacitance of the circular Schottky varactor can be found by calculating the net charge of the depletion layer from the numerically solved potential of the epitaxial layer [3, 4]. At millimeter wavelengths a first order correction term is normally included to the model of the junction capacitance as [3, 4, 5]

$$\begin{aligned} C_j &= \frac{\epsilon \pi R_0^2}{W}\left(1 + b\frac{W}{R_0}\right) \\ &= \frac{\epsilon \pi R_0^2}{W}\gamma_C, \end{aligned} \qquad (1)$$

where ϵ is the dielectric constant of the semiconductor, W is the width of depletion layer, b is numerical constant 1.5 and γ_C is the net correction term compared to the capacitance of the one-dimensional varactor. At submillimeter wavelengths an extra second order correction term should also be included in the model of the junction capacitance as [4]

$$C_j = \frac{\epsilon \pi R_0^2}{W}\left(1 + b_1\frac{W}{R_0} + b_2\frac{W^2}{R_0^2}\right), \tag{2}$$

where the numerical constants are $b_1 = 1.5$ and $b_2 = 0.3$.

2.2 Series resistance

The series resistance of the partially depleted epitaxial layer can be found from the geometrical resistance of the undepleted layer. The exact solution of the resistance depends from the width of the undepleted layer, which means that the series resistance is nonlinear [6]. However, if the nonlinearity of the series resistance is omitted, the efficiency of the multiplication is slightly decreased at low input power levels and remains almost the same at high power levels [7]. In computer simulations a constant series resistance is used in order to decrese the required time of the numerical analysis without decreasing the accuracy of the results too much. The resistance of the totally undepleted epitaxial layer with circular anode can be found analogically [8]

$$\begin{aligned} R_e &= \frac{\rho t_e}{\pi R_0^2}\frac{1}{t_e}\int_0^\infty \frac{\tanh(zt_e)\sin(zR_0)J_1(zR_0)}{z^2}dz \\ &= \frac{\rho t_e}{\pi R_0^2}\gamma_R, \end{aligned} \tag{3}$$

where ρ is the resistivity of the epitaxial layer and γ_R is the net correction term compared to the resistance of the one-dimensional varactor. For a varactor with a large anode compared to the thickness of the epitaxial layer ($R_0 \gg t_e$) the correction factor γ_R is 1 and for a very small anode the correction factor is

$$\gamma_R = \frac{\pi R_0}{4t_e}. \tag{4}$$

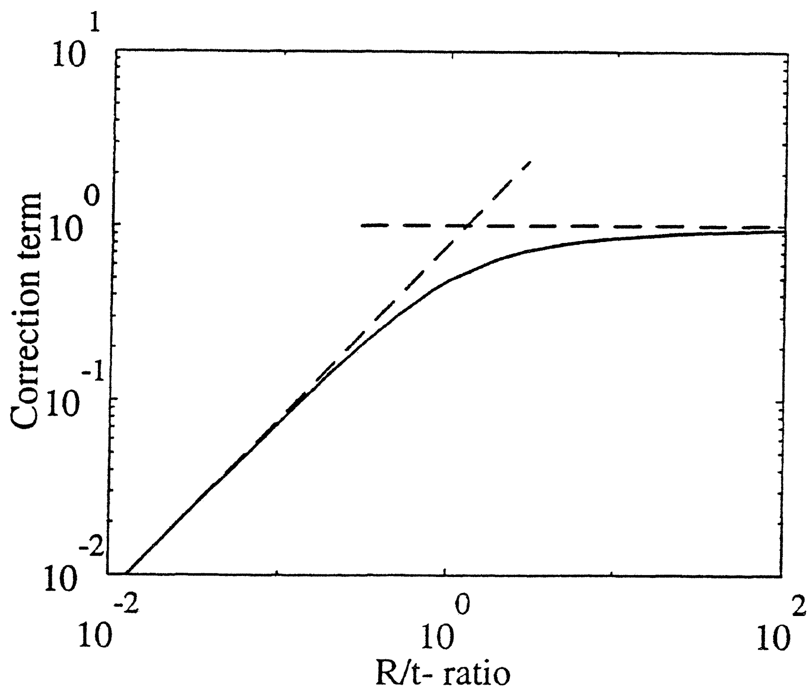

Figure 2: The net correction term of the series resistance γ_R.

For all R_0/t_e-ratios the net correction term can be easily found from the approximate formula

$$\gamma_R \approx \left[1 + \frac{4t_e}{\pi R_0}\right]^{-1}. \tag{5}$$

For a typical millimeter wave varactor the radius of the anode is about three times the thickness of the epitaxial layer and so the net correction term is about 0.73 (see Figure 2). The total series resistance of the varactor includes also the contact resistance (about 1 Ω) and the series resistance of the substrate layer. At frequencies above 100 GHz the plasma resonance should also be included to the model of the series resistance [6].

2.3 Electron velocity saturation

At millimeter and submillimeter wavelengths the maximum output power of a Schottky varactor frequency multiplier is strongly affected by the electron velocity saturation,

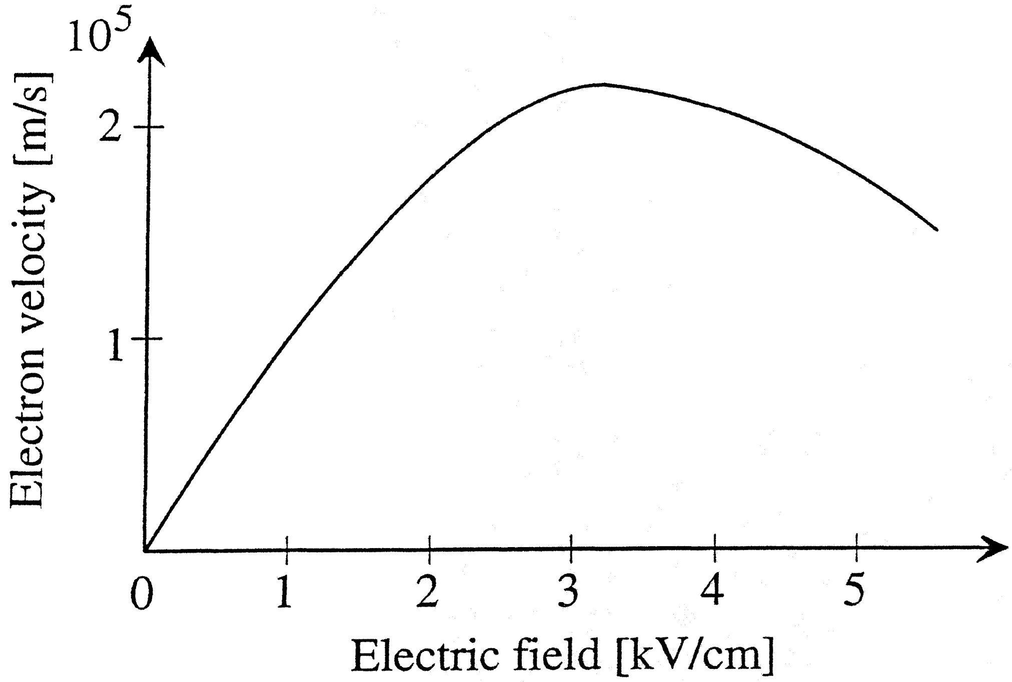

Figure 3: Schematic of the electron velocity in GaAs.

which takes place in GaAs at high electric fields (see Figure 3). At low electric fields the electron velocity is directly related to the electric field. In an intrinsic case the maximum electron velocity is about $2.2 \cdot 10^5$ m/s at electric field of 3.2 kV/cm. Kollberg *et al.* have modelled this saturation of the electron velocity by a nonlinear resistance, which increases as the function of the electron current of the varactor [9]. This model is empirical, because the formula of the nonlinear resistance ($R_i = aR_S i^6$) is found by fitting the results of numerical analyses to the experimental results. East *et al.* have recently presented a more physical model, where the electron conduction current has been limited by the maximum current of the varactor [10]

$$I_m = \pi R_0^2 N_D q v_m, \tag{6}$$

where N_D is the doping density, q is the charge of electron and v_m is the maximum velocity of electron . However this model is also empirical, because the value of maximum velocity ($3.5 \cdot 10^5$ m/s) has been obtained by fitting the results of the numerical analyses to the experimental results.

In this work a new model has been derived for the electron velocity saturation by limiting the velocity of the transition front between the depleted and undepleted layer by the maximum velocity of the electron

$$\left|\frac{\partial W}{\partial t}\right| < v_m. \tag{7}$$

The width of the depletion layer is given by

$$W = \sqrt{\frac{2\epsilon(\phi_{bi} - V)}{qN_D}}, \tag{8}$$

where ϕ_{bi} is built-in potential and V is the external voltage. When the electron conduction current required to pump the junction capacitance is

$$I = C_j \frac{\partial V}{\partial t} = C_j \frac{\partial V}{\partial W}\frac{\partial W}{\partial t}, \tag{9}$$

the maximum current of the diode is given by

$$\begin{aligned} I_m &= C_j \left|\frac{\partial V}{\partial W}\right| \left|\frac{\partial W}{\partial t}\right|_m \\ &= \frac{\epsilon\pi R_0^2 \gamma_C}{W}\frac{qN_D W}{\epsilon} v_m = \pi R_0^2 q N_D v_m \gamma_C. \end{aligned} \tag{10}$$

The edge effect is taken into account by the correction factor γ_C, which is also used for the junction capacitance. This means that the maximum current of the varactor depends on the actual area of the transition front between the depleted and undepleted layer. The maximum current of varactor given by equation (10) is always higher than the value obtained by using equation (6), because the area of the transition front is higher than the area of the varactor anode.

In static situation the maximum electron velocity in GaAs is about $2.2 \cdot 10^5$ m/s at eletric field of 3.2 kV/cm as mentioned before. However, during fast transients the electron velocity in GaAs can overshoot the steady-state value by several times [11, 12]. This velocity overshoot increases the maximum electron velocity at high frequencies. At millimeter wavelengths the maximum velocity can be assumed to be about $2.9 \cdot 10^5$ m/s [13].

3 Multiplier performance

We have tested the new model by analyzing the two diode balanced doubler for 160 GHz constructed by Erickson [14]. The varactor used in the doubler is a whisker contacted UVA 6P4 Schottky varactor, whose parameters are shown in Table 1. The doubler has been analysed by using the multiple reflections technique, where the linear part of the circuit is solved in frequency domain and the nonlinear part is solved in time domain [15].

The results of our analyses are shown in Figure 4. The efficiency has been calculated with optimum embedding impedances and with optimum bias voltage. The results of our theoretical analyses agree well with the experimental results, when the 0.5 dB input losses and the 0.8 dB output losses are taken into account. The equality between the numerical and experimental result is very good at high power levels, when the effect of the electron velocity saturation is high. The disagreement between the numerical results and the experiments at low input power levels can be partly explained by the measured VSWR at the input waveguide (VSWR is about 1.9 – 2.7 at input power levels 20 – 10 mW per diode) [16].

According to the simulation results the maximum electron conduction current during a

Table 1: Parameters of the Schottky varactor UVA 6P4.

Radius of the anode	R_0	3.2	μm
Thickness of the epitaxial layer	t_e	1.0	μm
Doping density	N_D	$3.5 \cdot 10^{16}$	1/cm^3
Electron mobility	μ	0.61	m^2/Vs
Series resistance	R_s	10.5	Ω
Junction capacitance at zero bias	C_0	21	fF
Break-down voltage	V_B	-20	V

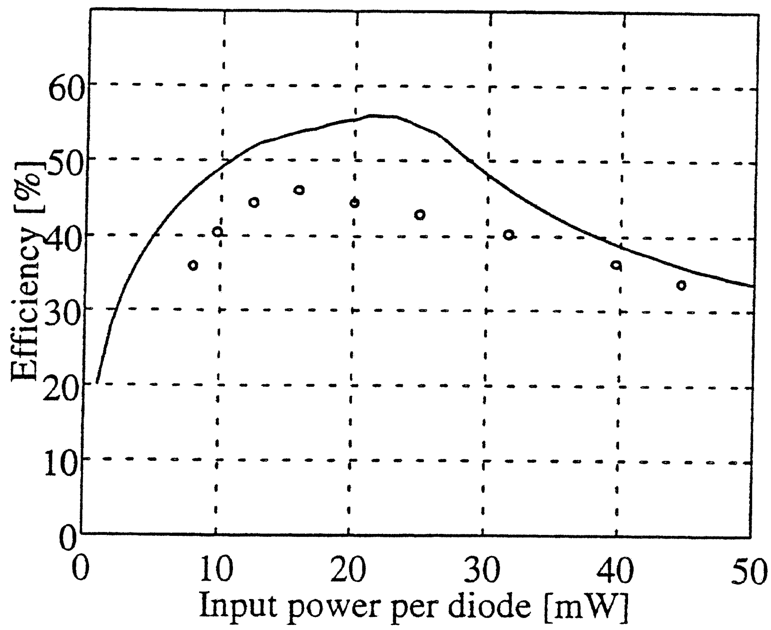

Figure 4: The maximum theoretical efficiency of a 160 GHz doubler. Measured results, after reduction of 0.5 dB input losses and 0.8 dB output losses, have also been plotted.

pump cycle is about 66 mA, when the input power is 60 mW per diode. This means that the maximum current obtained by using equation (6), which is about 52 mA , is exceeded by 25 % . In other words, when the edge effects have been taken into account, the increased area of the transition front between the depleted and undepleted layer helps to pump the junction capacitance of the Schottky varactor more efficiently than can be assumed, if equation (6) is employed. This means that our new model, which uses only physical parameters, works well without any extra fitting to the experimental results. Furthermore, our model can be used to analyse submillimeter wave frequency multipliers (doublers, triplers, quadruplers, quintuplers etc.), because the model is based on the physical parameters of the varactor and is independent from the multiplication factor and from the type of the Schottky varactor.

4 Conclusions

The equivalent circuit of the millimeter and submillimeter wave Schottky varactor is strongly affected by the edge effects of the small-area circular anode. In this work the electron velocity saturation has been modelled by limiting the velocity of the transition front between the depleted and the undepleted layers. By using this model the maximum conduction current of the varactor is given by the actual area of the transition front, which is always larger than the area of the anode. The equivalent circuit of the Schottky varactor includes also correction terms for the junction capacitance and for the series resistance.

The agreement between the theoretical results and the experimental results is good in the case of the two diode balanced doubler for 160 GHz, when physical parameters of the varactor are employed. The model can be used to analyse any submillimeter wave Schottky varactor frequency multiplier, because the model is based on the physical parameters of the varactor and is independent from the multiplication factor and from the type of the Schottky varactor.

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