Optimization of the Schottky Varactor for Frequency Multiplier Applications at Submillimeter Wavelengths

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Abstract—**Schottky varactor frequency multipliers are used to generate the all-solid-state local oscillator power at submillimeter wavelengths. The aim of this work was to develop a routine that can be used to optimize the electrical and geometrical parameters of the Schottky varactor in order to maximize the output power of the submillimeter wave Schottky varactor frequency multiplier. The optimization of the epitaxial layer thickness and doping density and the anode area significantly increases the maximum theoretical output power at the THz range.**

I. Introduction

One of the biggest challenges of the terahertz community is to develop a reliable all-solid-state power source with reasonable dc and rf efficiency [1]. The aim of this work is to develop an optimization routine for a submillimeter wave Schottky varactor frequency multiplier applications. The optimization routine includes three steps, and it can be used to optimize the electrical and geometrical parameters of the Schottky varactor in order to maximize the output power when the input power level, as well as the input and output frequencies, of the submillimeter-wave frequency multiplier are known. The new optimization routine is based on the novel equivalent circuit that includes a model for the effect of electron velocity saturation [2]–[4].

II. Optimization Routine

A. Optimization of the Thickness of the Epitaxial Layer

The first step of the optimization routine is to optimize the thickness of the epitaxial layer, t_e. This can be done by studying the voltage waveform of the pumped varactor and by using the information that the depletion layer front can not move faster than the maximum velocity of electrons v_m. As shown in Fig. 1, the voltage waveform of the pumped varactor includes three different kinds of regions: 1) a constant voltage region, 2) a negative voltage sweep region, and 3) a positive voltage sweep region. The slope of the voltage sweep depends on the device parameters as well as the multiplication factor. According to our results the time of the positive or negative sweep is about $1/2f_{out}$ [4]. The maximum modulation of the depletion layer width during this time is given by [5]

$$\Delta W = \frac{v_m}{2f_{out}}. \quad (1)$$

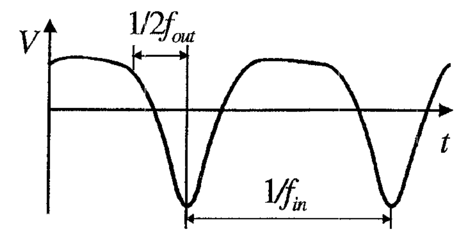

Fig. 1. Schematic of the voltage waveform of the pumped submillimeter-wave Schottky varactor.

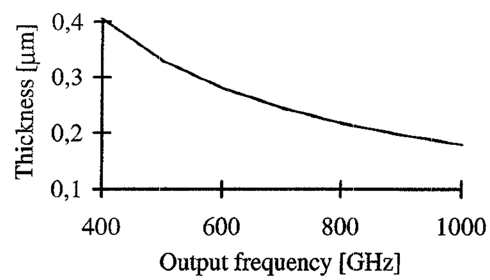

Fig. 2. Optimum thickness of the epitaxial layer.

In effective multiplication, the resistive multiplication due to the nonlinear junction conductance should be avoided. This means that during a pump cycle the width of the depletion layer should not become so small that the current begins to flow trough the depletion layer. The optimum thickness of the epitaxial layer, t_e, is found by adding few hundredths of a micrometer to the maximum modulation of the depletion layer width. When the maximum velocity of electrons is assumed to be $2.9 \cdot 10^5$ m/s, the optimum thickness of the epitaxial layer of the Schottky varactor frequency multiplier for 1 THz is about 0.2 μm, as shown in Fig. 2.

B. Optimization of the Doping Density of the Epitaxial Layer

The second step of the optimization routine is to optimize the doping density of the epitaxial layer, N_d. This can be done by comparing the advantages and disadvantages due to the increased doping level. The decreased series resistance and increased current handling capability raises the efficiency of the multiplication when the doping density is increased. At

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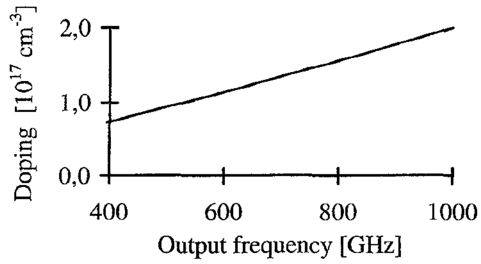

Fig. 3. Optimum doping density of the epitaxial layer.

the same time, however, the breakdown voltage is decreased, which reduces the maximum possible voltage modulation area. A useful balance is reached when the doping density is optimized so that a breakdown is avoided and the epitaxial layer is totally undepleted. Thus, the optimum doping density is given by [6]

$$N_d = \frac{E_C \epsilon_s}{q t_e} \tag{2}$$

where E_C is the critical field at breakdown (about $7.0 \cdot 10^4$ kV/m for doping density 10^{17} cm^{-3}), ϵ_s is the dielectric constant of the semiconductor, and q is the charge of an electron. The calculated optimum doping density of the epitaxial layer versus output frequency is shown in Fig. 3.

C. *Optimization of the Anode Radius*

The third step of the optimization routine is to optimize the radius of the anode, R_0. This step can be done by maximizing the output power of the multiplier. The optimum area of the anode depends on the input power level of the multiplier so that the optimum area increases when the input power level increases. The optimum size is found by analyzing the entire frequency multiplier circuit by employing the harmonic balance method with the novel equivalent circuit [5]. This means that while the radius of the anode is optimized, the circuit parameters of the frequency multiplier are also optimized.

III. Optimization of a Tripler for 1 THz

The above optimization routine can be employed to optimize any submillimeter-wave Schottky varactor frequency multiplier. As an example, we have optimized a tripler for 1 THz, because the multiplier chain utilizing the tripler for 1 THz preceded by either a tripler for 330 GHz or a doubler for 165 GHz, followed by a doubler for 330 GHz, seems to be a good choice to generate the all-solid-state local oscillator power for frequencies near 1 THz. The optimum thickness of the epitaxial layer at 1 THz is about 0.2 μm, as shown in Fig. 2. The optimum doping density of the epitaxial layer is about $2.0 \cdot 10^{17}$ cm^{-3}, as shown in Fig. 3. The optimum density is significantly higher than the value of $1.0 \cdot 10^{17}$ cm^{-3}, which is conventionally used at submillimeter wavelengths. The increased doping density increases the current handling capability as well as decreases the series resistance of the varactor, which means that the efficiency of the multiplication increases. The radius of the anode is optimized by analyzing the entire multiplier circuit with five different sizes of the anode and with three different input power levels. As shown in Fig. 4, the optimum anode radius is 1.1, 1.2, and 1.3 μm with input power levels of 3.0, 4.0, and 5.0 mW, respectively. If the maximum all-solid-state input power at 330 GHz is assumed to be 4.0 mW, the theoretical output power at 1 THz is 0.65 mW. This maximum output power is about 6 dB higher than the power of 0.15 mW, which can be generated by employing the conventional UVa 2T2 Schottky varactor [5].

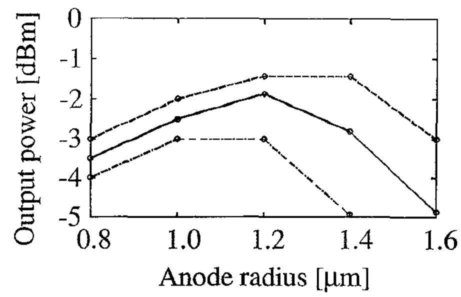

Fig. 4. Maximum theoretical output power at 1 THz versus anode diameter and input power levels of 3, 4, and 5 mW (dot-dashed, solid, and dashed lines).

These results remain to be verified by experiments, but it seems that the state-of-the-art output power of 60 μW at 1 THz [7] can be improved by optimization. Recently, Zimmermann [8] has experimentally obtained improved efficiencies at THz range when using increased epitaxial layer doping density and decreased epitaxial layer thickness. This is in good accordance with our theoretical results.

IV. Conclusion

In this work, we have developed a three-step routine that can be used to optimize the electrical and geometrical parameters of a submillimeter-wave Schottky varactor. According to our results, the optimization increases significantly the maximum theoretical output power at THz range.

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