Design of Heterostructure Barrier Varactor Frequency Multipliers at Millimeter-wave Bands

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Abstract— **A physics-based CAD tool for the design of heterostructure barrier varactor (HBV) frequency multipliers is presented in this work. This design tool is based on the Harmonic Balance method together with a physics-based drift-diffusion numerical device simulator. A joint optimization of the circuit parameters and the structure of the HBV diodes maximises the conversion efficiency at millimeter-wave bands. Different material systems have been considered for the designs: $AlGaAs/GaAs$, and $InGaAs/InAlAs$. An initial effort for validation has been carried out with measurements published in the literature for a 300 GHz $GaAs/AlGaAs$-based tripler, and a 250 GHz $InGaAs/InAlAs$-based tripler with very promising results.**

Index Terms— **CAD, Heterostructure Barrier Varactor (HBV), harmonic balance, submillimeter-wave technology, frequency multiplier.**

I. Introduction

Varactor frequency multipliers play a key role in developing solid-state power sources at terahertz frequencies. Heterostructure barrier varactors represent a very interesting technological alternative to traditional Schottky diodes providing an alternative for the fabrication of frequency multipliers at millimeter-wave and submillimeter-wave bands [1], [2].

An HBV is a symmetric device composed of a high band-gap undoped or sligthly doped semiconductor (*barrier*), placed between two low band-gap highly doped modulation layers. When an external bias is applied across the device, electrons are accumulated on one side of the barrier and deplected on the opposite side providing a voltage-dependent depletion region in one of the modulation layers. When the structure presents symmetry, an even C-V characteristic is obtained

HBV diodes show several advantages for the implementation of frequency multipliers:

- An easier power handling due to the possibility of stacking several barriers in a single device.
- The achievement of odd multiplication factors with no need of filtering the even harmonics of the RF signal.
- No bias is required for HBV multipliers with odd multiplication factors, contrarily to Schottky ones.

The integration of numerical simulators for active devices into circuit simulators avoids the need an equivalent-circuit model extraction providing another degree of freedom to improve the performance of circuits because they can be designed from both the device and the circuit point-of-view. The scope of this paper is to present a design tool for HBV-based multipliers at millimeter-wave and submillimeter-wave bands employing a physics-based HBV numerical model coupled with an external circuit simulator analogous to that one described for Schottky multipliers [3].

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Our HBV simulator incorporates accurate interface conditions to account for the most important current transport mechanisms in an HBV: Thermionic emission of electrons over the barrier and electron tunnelling through it. The dominating one is determined by the temperature, bias voltage, effective barrier height, doping and thickness of the barrier and modulation layers. The physics-based model also incorporates different materials systems: $AlGaAs/GaAs$ or $AlAs/AlGaAs/GaAs$ on $GaAs$ substrate, $InAlAs/InGaAs$ or $AlAs/InAlAs/InGaAs$ on InP substrate.

The validation of the numerical simulator has been performed with experimental results for devices and multipliers fabricated at the University of Virginia (UVa), Charlottesville (USA), and at Chalmers University of Technology, Göteborg (Sweden) [1], [2], [4], [5].

The physics-based model for HBVs is presented in Section II. The validation of this analysis and design tool is carried out in Section III. An analysis of different critical aspects of HBV-based tripler design is accomplished in Section IV. Some conclusions are drawn in section V.

II. HBV Physical Device Model

The electrical performance of the HBV diodes is investigated with a one-dimensional (1-D) drift-diffusion formulation. The recombination rate is modelled by the Shockley-Read-Hall recombination, and the generation rate is restricted to impact ionization [6].

Our physics-based model incorporates accurate boundary and interface conditions. We impose Dirichlet's boundary conditions at metal contacts for Poisson's and carrier continuity equations [6]. On the other hand, thermionic and thermionic-field carrier transport at the barriers is imposed at the different interfaces caused by the material composition discontinuities [7].

Tunelling transport through the barrier is significant especially for HBV diodes with high doping in the modulation layer. In this model, the time-independent Schrödinger's equation is solved using the transfer matrix approach [8] particularized for HBV barriers. The same grid defined for Poisson's and carrier continuity equations is used for Schrödinger's equation.

The coupling of the physical device model and the circuit simulator is omitted in this paper but a detailed description can be found in [3].

III. Validation of The Physical Model

Our physical model has been validated with measurements for several HBV diodes with different material composition, modulation layer thickness, doping level, and area. The parameters for diodes analyzed in this paper are provided in Table I, [1], [9].

TABLE I
HBV DIODE PARAMETERS FOR DEVICES ANALYZED

Diode and Composition Materials	Modulation layer		Barrier
	Doping (cm^{-3})	Length (nm)	Length (nm)
UVa SHBV [1]: $Al_{0.7}Ga_{0.3}As/GaAs$	10^{17}	335	21.5
UVa-NRL-1174 (4-barrier)[1]: $Al_{0.7}Ga_{0.3}As/GaAs$	$8 \cdot 10^{16}$	250	20
SHBV [9]: $AlAs/In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$	10^{17}	300	5/3/5

A good agreement for I-V and C-V characteristics is demonstrated for $AlGaAs/GaAs$ HBV-based diodes: Fig. 1(a) represents the DC characteristics for a single-barrier HBV, and Fig. 1(b) shows the DC performance for a four-barrier HBV. For these simulations, the barrier height has been fitted as was suggested in [1]: $\Delta E_c = 300\ meV$ for $Al_{0.7}Ga_{0.3}As/GaAs$ barriers. There is also a good agreement for $InGaAs/InAlAs$ HBV diodes. However, no fitting parameters have been used for this device.

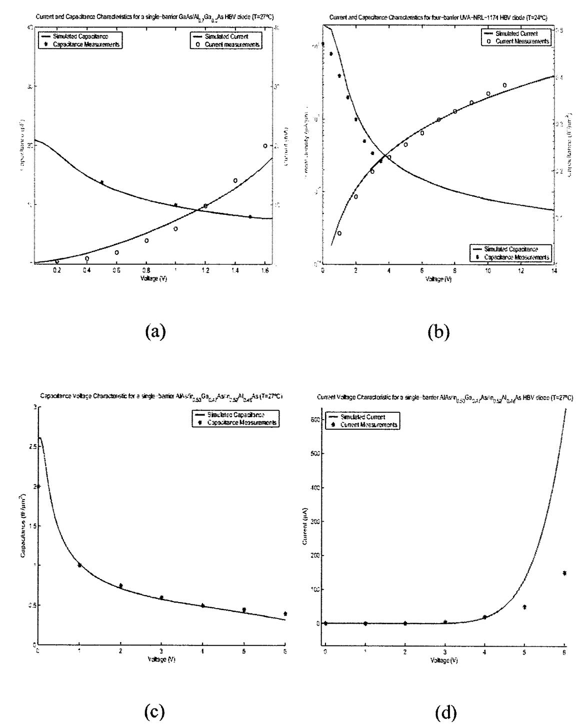

Fig. 1. Simulated and measured I-V and C-V characteristics for HBV diodes [1], [2], [9]. The diode parameters are indicated in Table I.

We have also performed RF simulations for two frequency triplers reported in the literature [1], [5] based on devices of table I. Efficiency versus input power for the $AlGaAs/GaAs$ SHBV tripler at 300 GHz is analysed in Fig. 2. Efficiency levels obtained are in good agreement with experimental data: A $\sim$ 10% efficiency is obtained, while the maximum experimental efficiency [10] for the same device and in a similar range of input frequency, 70-100 GHz, is about 13% at 5 mW of input power. The load impedance at the output $Z_g(3f_o)$ was optimized for maximum efficiency, $Z_g(3f_o) \approx (6 + j8)\Omega$, while at the fundamental frequency the load is matched for each input power. Regarding the $InGaAs/InAlAs$ HBV-based tripler, we obtained a $\sim$ 13% in good agreement with scaled measures for the same structure with four barriers [5] as showed in Fig 3.

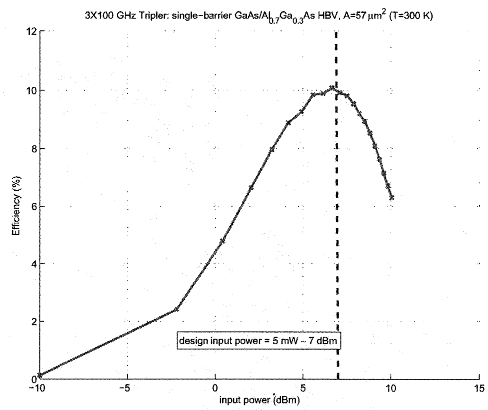

Fig. 2. Simulated efficiency versus input power for a single barrier $AlGaAs/GaAs$ HBV-based frequency tripler. The diodes parameters are indicated in Table I.

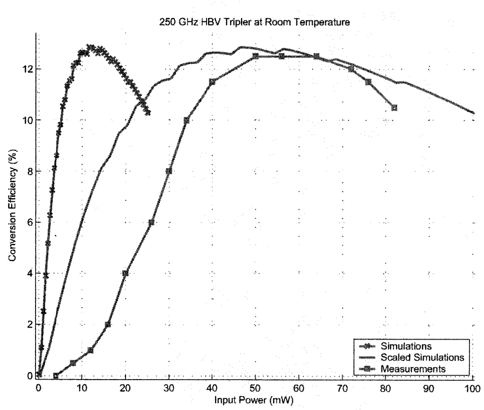

Fig. 3. Simulated and measured efficiency versus input power for $InGaAs/InAlAs$ single-barrier HBV-based frequency multiplier [5]. The diode parameters are indicated in Table I.

The selection of the impedance for the third harmonic is crucial for frequency triplers. The optimum values for the selected input frequency and power level are summarized in Table II, together with the matched impedance values for the fundamental frequency.

TABLE II
MAXIMUM CONVERSION EFFICIENCY AND IMPEDANCE LEVELS OF HBV-BASED FREQUENCY TRIPLERS.

Multiplier	$\eta(\%)$	$Z(3f_o)\ \Omega$	$Z(f_o)\ \Omega$
UVa SHBV: $(Al_{0.7}Ga_{0.3}As/GaAs)$ 3X100GHz , 5 mW	$\sim 10\%$	$6+j8$	$3+j22$
SHBV [9]: $AlAs/In_{0.52}Al_{0.48}As/$ $In_{0.53}Ga_{0.47}As$ 3X82.5 GHz, 12.5 mW	$\sim 13\%$	$9+j13$	$3+j21$

IV. HBV-BASED MULTIPLIERS: DEVICE, CIRCUITAL AND THERMAL ASPECTS.

The capabilities of our simulation tool for the analysis and design of frequency multipliers have been demonstrated for single or multiple barrier HBVs, with different material compositions, and in a wide range of input powers and frequencies. In this section, an in-depth analysis on the influence of the device structure and some limiting mechanisms is illustrated for the UVa SHBV-based frequency 3X100 GHz tripler presented previously.

A. Impact of the device structure

First of all we must select the number of barriers taking into account the required power handling. When the number of barriers in an HBV is increased, the maximum efficiency is achieved for higher input power levels, Fig. 4, and this increment is approximately proportional to the number of barriers. The matched impedance at the fundamental frequency is also scaled by the number of barriers. The multiplier circuit is more sensitive to changes in the embedding impedances at low-input power levels as compared to high-input power levels.

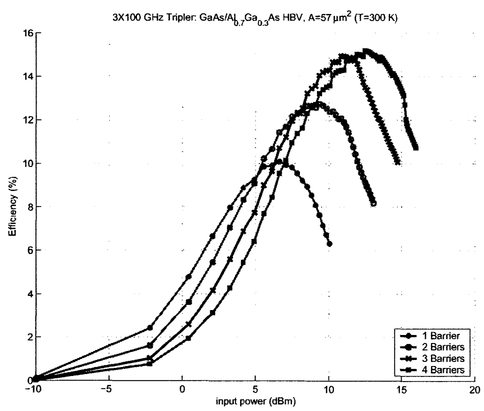

Fig. 4. Simulated efficiency versus input power for a 3x100 GHz frequency multiplier and different number of barriers. The basic diode parameters has been presented in Table I.

Once the number of barriers is selected, the device structure must be optimised. For thin and highly doped modulation layers, the maximum of efficiency increases and is achieved for higher input powers, Fig. 5.

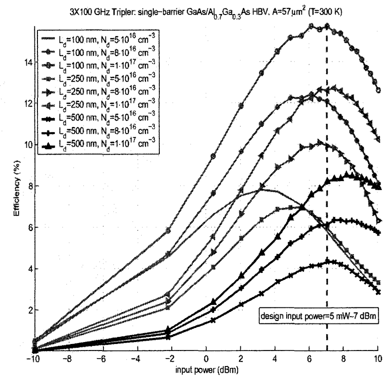

Fig. 5. Simulated efficiency versus input power for a single-barrier HBV-based 3x100 GHz frequency multiplier for different modulation layers' lengths (L_d) and dopings (N_d).

Finally, the area can be selected in order to get the maximum efficiency for the selected input power level.

B. Impact of avalanche breakdown

Figure 6 presents the influence of the carrier generation by impact ionisation on the tripler performance. When the voltage swing is high enough for reaching the breakdown voltage, a significant decrease in the efficiency is caused. Therefore, when the modulation layers are designed, the breakdown volatege of the HBV must be taken into account for power handling design.

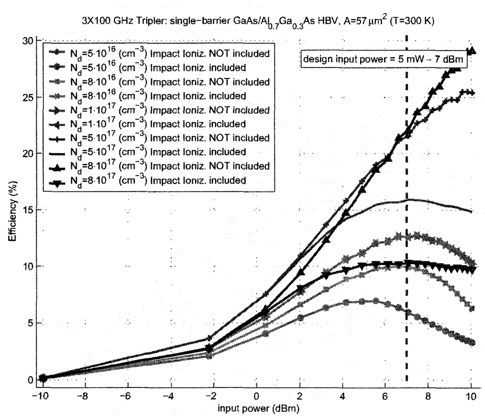

Fig. 6. Impact of avalanche breakdown on efficiency versus input power characteristic for a single-barrier HBV-based 3x100 GHz frequency multiplier as a function of modulation layer doping.

C. Impact of Device Temperature

It has also been demonstrated in [11], [12] that the increase in the temperature has a crucial responsibility on the decrease in the efficiency for HBV-based frequency multipliers, 7. In fact, self-heating could be the limiting mechanism for frequency multiplication if a proper thermal design is not carried out [11].

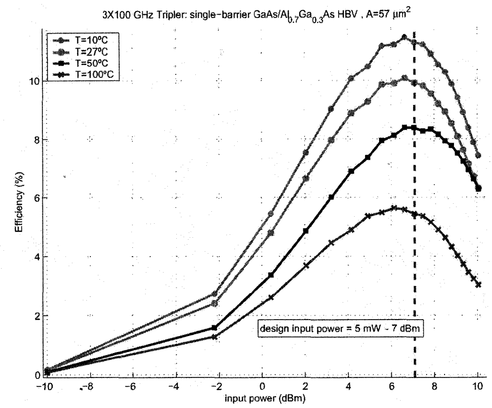

Fig. 7. Simulated efficiency versus input power for a single-barrier HBV-based 3x100 GHz frequency multiplier as a function of room temperature.

D. Loads at the fifth harmonic

One of the most important advantages of HBV-based multipliers is the generation of odd harmonics without filtering the even ones. This capability is based on the symmetry of the electrical characteristics for unbiased devices. Thus, the load impedances for even harmonics have no effect on the efficiency characteristic. However, the fifth harmonic load impedance has a significant influence on the tripler conversion efficiency as illustrated in Fig. 8. In this figure, the evolution of efficiency versus imaginary part of the embedding impedance for different real parts is presented.

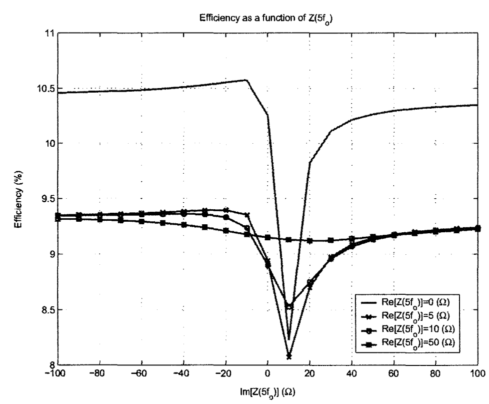

Fig. 8. Simulated efficiency versus input power for a single-barrier HBV-based 3x100 GHz frequency multiplier as a function of the fifth harmonic impedance.

V. Conclusions

The flexibility of our CAD tool allows the joint design of the internal HBV structure and the external circuit. The advantages of this integrated strategy has resulted in two designed triplers with good agreement between simulated results and experimental data at frequencies up to 300 GHz. This tool offers the opportunity to understand some limiting mechanisms in HBVs, such as self-heating effects and avalanche breakdown, and to mitigate them through a proper design.

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