Numerical Physical Model for Heterostructure Barrier Varactors

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Abstract— **A physics-based CAD tool for the design of heterostructure barrier varactors (HBV) is presented. We analyse the impact of the material system and device structure on the limiting transport mechanisms in HBVs and on HBV-based frequency tripler performance.**

Index Terms—**CAD, heterostructure barrier varacto, 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 millimetre-wave and submillimeter-wave bands [1], [2].

An HBV is a symmetric device composed of a high bandgap 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 depleted 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 electrical performance characteristics of HBV diodes have been studied with a one-dimensional physics-based HBV numerical model. It combines conventional drift-diffusion formulation with thermionic and thermionic-field emission currents imposed at the interface between layers. Tunnelling transport through the barriers is significant especially for HBV diodes with high doping in the modulation layer. The time-independent Schrödinger's equation is solved using the transfer matrix approach in order to calculate the transmission coefficient through the different barriers in the device.

This simulation tool incorporates different materials systems (*AlGaAs/GaAs* or *AlAs/AlGaAs/GaAs* on *GaAs* substrate, *InAlAs/InGaAs* or *AlAs/InAlAs/InGaAs* on *InP* substrate), non-constant doping and composition profiles for each layer, as well as variable number of barriers. This tool offers the possibility to understand some limiting mechanisms in HBVs, such as tunnelling transport through the barriers, avalanche breakdown due to impact ionization, or self-heating effects, and to mitigate them through a proper design.

This physics-based simulator has been integrated into an in-house circuit simulator based on the harmonic balance method. The integration of numerical simulators for active devices into circuit simulators avoids the need of equivalent-circuit model extraction, and provides another degree of freedom to improve the performance of circuits because they can be designed from both a device and a circuit point-of-view.

The physics-based model for HBVs is presented in Section II. An analysis of different critical aspects in the design of HBVs is accomplished in Section III. The influence of temperature in HBV performance is analysed in section IV. Some conclusions are drawn in section V.

II. HBV PHYSICAL DEVICE MODEL

The harmonic balance method (HBM) is the most common technique for the design of large-signal nonlinear microwave circuits. The HBM depends critically on the accuracy of the nonlinear element model employed in the analysis. This model must be valid for a wide range of frequencies and embedding impedances. The electrical and RF performance characteristics of millimetre-wave and submillimeter-wave HBV diodes and frequency multiplier circuits investigated here are based on an accurate physical model, which combines drift-diffusion current transport [3] with thermionic and thermionic-field emission currents at the interfaces caused by material composition discontinuities [4].

The electrical performance of the HBV diodes is investigated with a one-dimensional (1-D) drift-diffusion formulation: The governing equations are Poisson‘s equation, and the carrier continuity equations for electrons and holes. The recombination rate is modelled by the Shockley-Read-

Manuscript received 21 April 2009. This work was supported in part by the Spanish National Research Programme under project TEC2005-07010-C02-01/TCM.

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Hall recombination, and the generation rate is restricted to impact ionization [3].

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 [3]. On the other hand, thermionic and thermionic-field carrier transport at the barriers is imposed self-consistently at the different interfaces caused by material composition discontinuities [4].

Tunnelling transport through the barriers is significant especially for HBV diodes with high doping in the modulation layer. The time-independent Schrödinger's equation is solved using the transfer matrix approach [5] in order to calculate the transmission coefficient through the different barriers in the device.

Newton's method is used for the solution of the coupled system of equations obtained after the discretization of the partial differential equations through finite difference methods at the points of a nonuniform mesh.

Our physical model has been validated with measurements from several HBV diodes with different material compositions, modulated layer thicknesses, doping levels, and areas. The parameters for these diodes are provided in Table 1, and references [1], [6].

Table 1 HBV diode parameters

HBV Composition	Modulation layer		Barrier
	Doping (cm^{-3})	Length (nm)	Length (nm)
UVa-NRL-1174 [1] $Al_{0.7}Ga_{0.3}As/GaAs$	$8x10^6$	250	20
SHBV[6] $AlAs/In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$	10^{17}	300	5/3/5

A good agreement for I-V and C-V characteristics was presented in a previous contribution [7] for the diodes of Table 1.

III. DESIGN OF HBV DIODES

The first step in the design of a frequency multiplier is the optimisation of the active device. The nonlinearity used in HBVs working as a frequency tripler or quintupler is the capacitance. Therefore, the designer must maximise the capacitance swing for a given input power, while reducing the DC current consumption. The minimisation of the current will result in a reduction of the thermal problems and an improvement of the reliability of the circuit.

Figure 1 shows the influence of the Al content of the barrier on the I-V characteristic for a single barrier diode UVa-NRL-1174, Table 1. The higher the Al content is, the higher the discontinuity in the conduction band is, and, therefore, the current through the barrier diminishes. However, the C-V characteristic is not significantly affected by the variation of the Al content of the barrier.

A higher reduction of the current through the barrier can be obtained by using different material for the HBV. Figure 2 compares two SHBVs (single HBV) for the material systems described in Table 1. The conduction band discontinuity created by the heterostructure $AlAs/In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ is higher than for the $Al_{0.7}Ga_{0.3}As/GaAs$ barrier. Therefore, the current through the barrier presents an additional reduction.

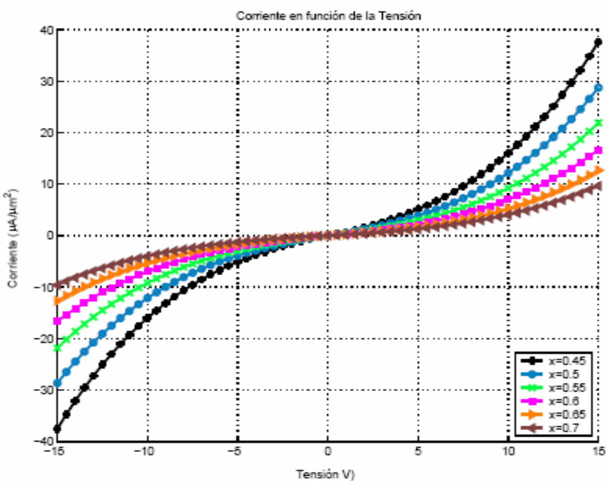

Figure 1.- I-V characteristic of a SHBV $Al_xGa_{1-x}As/GaAs$ as a function of the Al composition, Table 1.

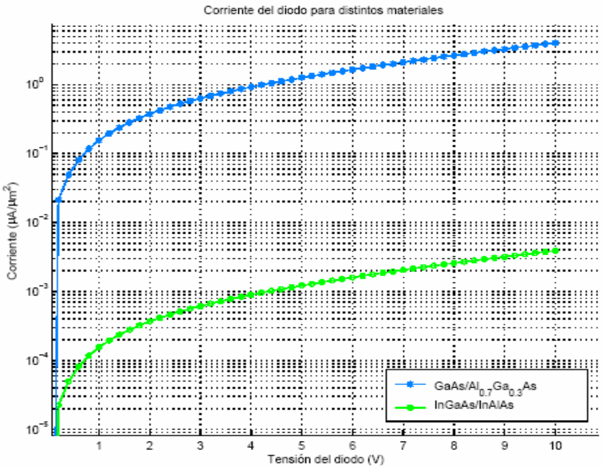

Figure 2.- I-V characteristics of a SHBV $Al_{0.7}Ga_{0.3}As/GaAs$ and a SHBV $AlAs/In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$, Table 1.

The second step consists of selecting the thickness of the modulation layer and the barrier. The thickness of the modulation layer must accommodate the maximum length of the depletion region for a given input power. If this rule is not accomplished, the capacitance swing is reduced, Figure 3. On the other hand, the thickness of the barrier must be thin enough to improve the capacitance swing, Figure 4, but thick enough to reduce the transmission probability for tunnelling transport through the barrier.

The final step is the selection the number of barriers taking into account the available input power. HBVs can stack several barriers in a single device easily in order to improve the power handling capability. Figure 5 and Figure 6 shows the I-V and C-V characteristics of the diode UVa-NRL-1174 [1] based on the material system $Al_{0.7}Ga_{0.3}As/GaAs$ as a function of the number of barriers. Both the current and the capacitance are inversely scaled as a function of the number of barriers.

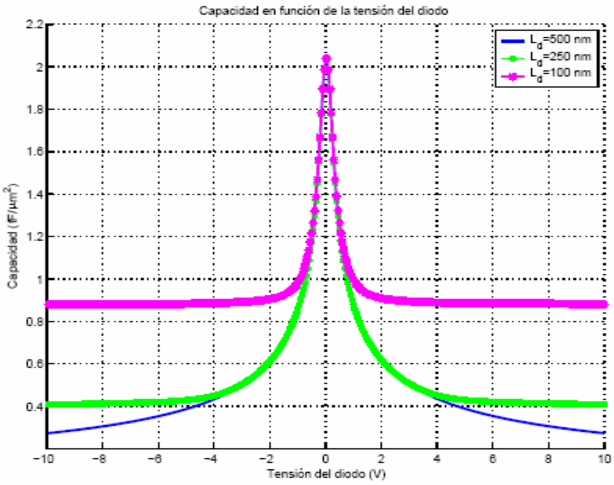

Figure 3.- C-V characteristic for the SHBV $Al_{0.7}Ga_{0.3}As/GaAs$ as a function of the modulation layer thickness. Other parameters as in Table 1.

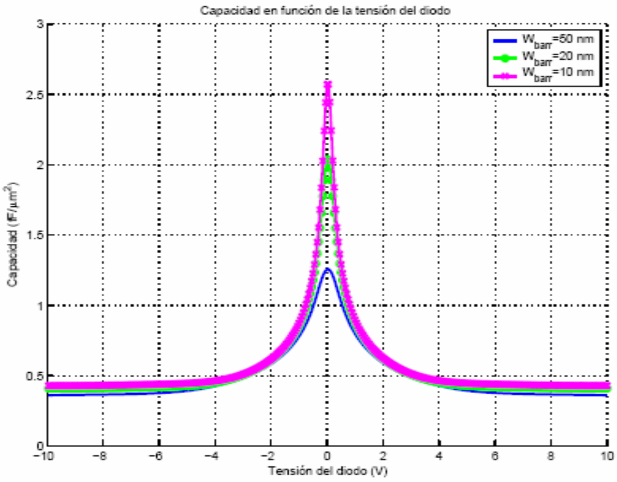

Figure 4.- C-V characteristic for the SHBV $Al_{0.7}Ga_{0.3}As/GaAs$ as a function of the barrier layer thickness. Other parameters as in Table 1.

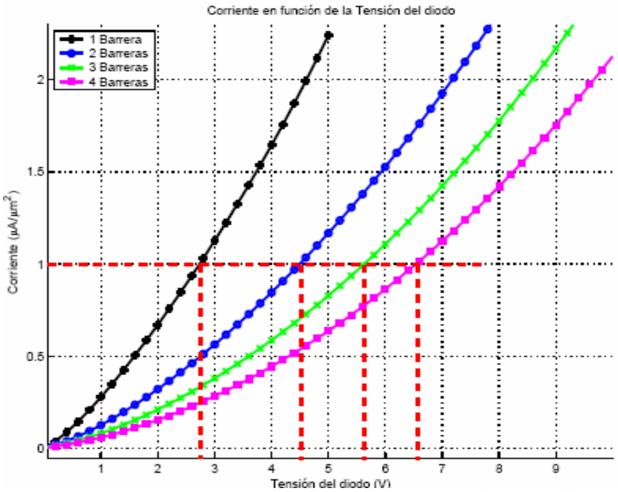

Figure 5.- I-V characteristic as a function of the number of barriers for $Al_{0.7}Ga_{0.3}As/GaAs$ UVa-NRL-1174 [1].

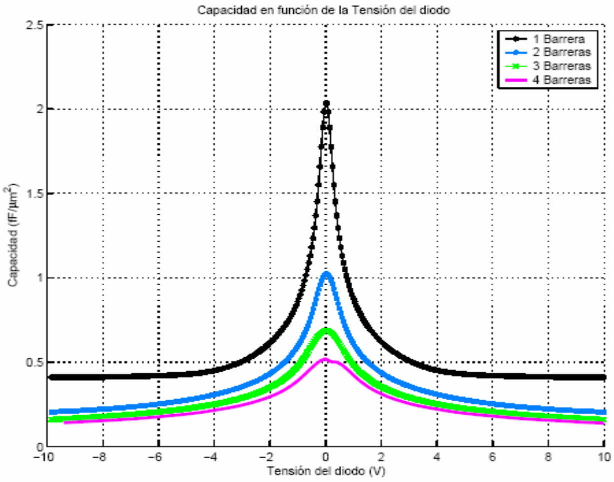

Figure 6.- C-V characteristic as a function of the number of barriers for $Al_{0.7}Ga_{0.3}As/GaAs$ UVa-NRL-1174 [1].

IV. INFLUENCE OF TEMPERATURE IN HBV CHARCACTERISTICS

Once the structure of the device is fixed, and before the optimisation of the embedding circuit which was presented in [7] following the approach described in [8] for Schottky diodes, it is important to analyse the impact of the temperature on the device performance. In fact, self-heating could be the limiting mechanism for frequency multiplication if a proper thermal design is not carried out [9]. Figure 7 and Figure 8 present the degradation of the diode characteristics as a function of ambient temperature. I-V characteristics are more affected because the thermionic emission current through the barrier is enhanced.

It has been demonstrated in [9], [10] that the increase in the temperature has a crucial responsibility on the decrease in the efficiency for HBV-based frequency multipliers, as it is shown in Figure 9 for a 3x100 GHz tripler designed with the $Al_{0.7}Ga_{0.3}As/GaAs$ SHBV described in table 1.

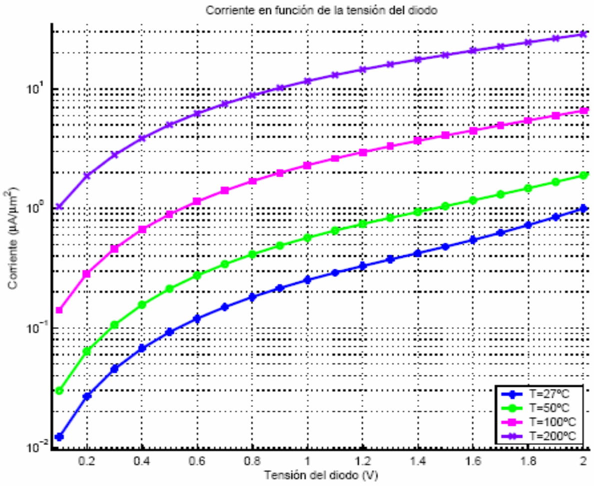

Figure 7.- I-V characteristic for the SHBV $Al_{0.7}Ga_{0.3}As/GaAs$ as a function ambient temperature. Other parameters as in Table 1.

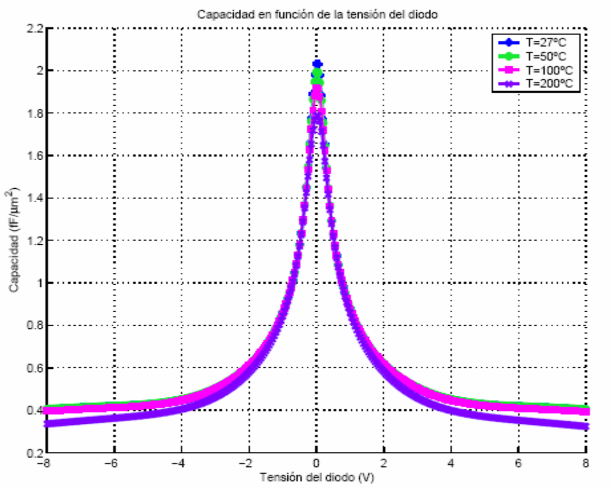

Figure 8.- C-V characteristic for the SHBV $Al_{0.7}Ga_{0.3}As/GaAs$ as a function ambient temperature. Other parameters as in Table 1.

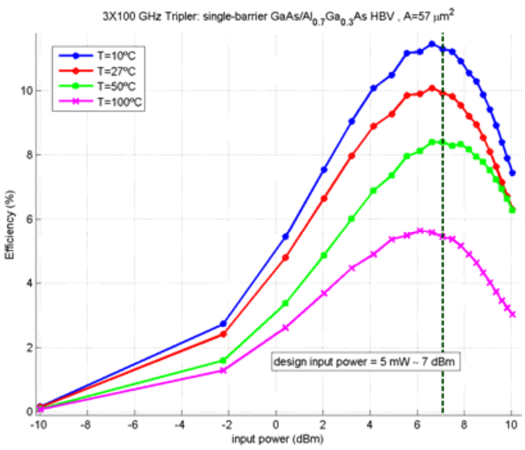

Figure 9.- Simulated efficiency versus input power for a SHBV-based 3x100 GHz frequency tripler as a function of room temperature. The SHBV is the $Al_{0.7}Ga_{0.3}As/GaAs$ diode described in Table1.

V. CONCLUSION

The flexibility of our CAD tool allows the joint design of the internal HBV structure and the external circuit. This tool offers the opportunity to perform an in-depth study of the impact of material system and device structure on the limiting transport mechanisms in HBVs and on HBV-based frequency multiplier performance.

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