Journal of Physics: Conference Series **193** (2009) 012021 doi:10.1088/1742-6596/193/1/012021

RF doubling and rectification in three-terminal junctions: experimental characterization and Monte Carlo analysis

I. Iñiguez-de-la-Torre[1], T. González[1], D. Pardo[1], C. Gardès[2], Y. Roelens[2], S. Bollaert[2], A. Curutchet[3], C. Gaquiere[2] and J. Mateos[1]

[1]Departamento de Física Aplicada, Universidad de Salamanca,
Plaza de la Merced s/n, 37008 Salamanca, Spain
[2]Institut d'Electronique, de Microélectronique et de Nanotechnologie (IEMN),
Université de Lille, UMR CNRS 8520, BP 60069, 59652 Villeneuve d'Ascq, France
[3]Laboratoire IMS, Université Bordeaux 1,
351 Cours de la Libération, 33405 Talence, France

E-mail: indy@usal.es

Abstract. The feasibility of three-terminal junction devices for frequency doubling and rectification reaching the terahertz range is studied both experimentally and numerically (by means of Monte Carlo simulations). Experiments at room temperature up to 94 GHz for detection and to 4 GHz for doubling and phase detection are shown. The influence of the width of the branches and the shape of the junction (T-shaped vs. Y-shaped) on the frequency response of the devices has been studied. Cut-off frequencies found for frequency doubling are lower than for the rectifying operation of the devices. This difference is attributed to the slow characteristic time of carrier penetration into the stem.

1. Introduction

Nanometer sized Three-Terminal Junctions (TTJs) [1] based on high mobility semiconductors are emerging as potential building blocks for analog and digital integrated circuits. Ballistic transport of electrons inside these structures results in an attractive nonlinear response [2]. In virtue of the parabolic behavior of the stem voltage when biasing the left and right branches in push-pull fashion, several applications like rectification, frequency doubling and mixing, and operation as digital logic gates are possible [3]. Although their static behavior is already well understood, not much attention has been paid till now to the study of their RF response. Owing to its small size (and intrinsic high impedance), the cutoff frequency of these devices is mainly limited by its RC time constant. The aim of this work is to analyze the dependence of the cutoff frequency of TTJs on their geometry: width of the horizontal and vertical branches and angle between the left and right branches (T-shaped vs. Y-shaped junctions). To fully understand the device operation and predict its intrinsic cutoff frequencies, a Monte Carlo (MC) simulator is used. Experimental results of TTJs working as detectors at 94 GHz and as frequency doublers and phase detectors at 4 GHz are also shown.

2. Monte Carlo simulations

TTJs are fabricated by defining the boundaries of three connecting semiconductor channels on the top of a heterolayer. In this case we use a high In content InGaAs channel to get maximum mobility. Our simulation tool is a Monte Carlo code employed in previous works to understand the physics of TTJs, successfully reproduce the experimental measurements and optimize the design of several kinds of ballistic nanodevices [2, 5-8]. The results shown in this paper have been obtained with a surface charge profile calculated at equilibrium conditions by means of the self-consistent model presented in [6-7], then used when a voltage (DC or AC) is applied to the different branches. By using this "frozen" equilibrium surface charge profile we assume that the capture/emission times of the surface states (typically of about 1 μs) is several orders of magnitude longer than the maximum period used for exciting the TBJ (1 ns). The geometry of the simulated devices is sketched in figure 1. The bias is applied in push-pull fashion to the left and right branches and the potential at the bottom of the vertical branch, called V_C, is measured (or simulated) in open circuit conditions. For the T-shaped junctions we consider two parameters to analyze their influence on the dynamic response: the width of the horizontal branches W_{HOR} and the width of the vertical stem W_{VER}.

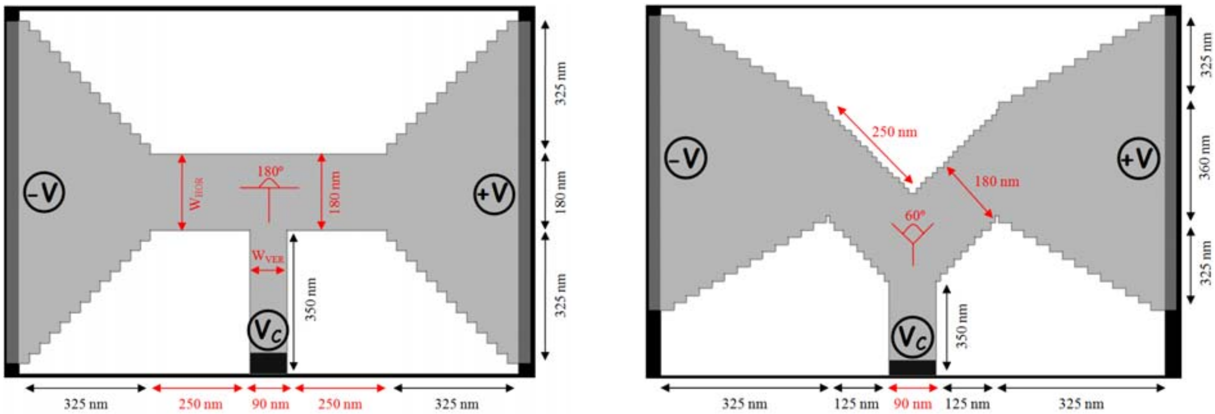

Figure 1. Topology of the simulated structures. (a) T-shaped junction and (b) Y-shaped junction

Figure 2 shows the DC value of V_C and the current flowing through the horizontal branches for several junctions. When the width of the vertical branch is reduced, the parabolicity in the bell-shape of the V_C-V curves is enhanced, while providing a similar current (as expected since W_{HOR} is the same [6]). On the other hand, the stem voltage values are more negative in the Y-shaped junction than in the T-shaped one because of the enhanced electron penetration into the vertical branch. A narrower horizontal branch leads to less negative values of V_C (and obviously to lower current). This is not consistent with experimental measurements (that show an enhancement of the bell shape of V_C vs. V) due to the bias dependence of the surface charge profile (explanation can be found in Ref. 7). The "frozen" equilibrium surface charge profile is used here in order to simplify the analysis of the results.

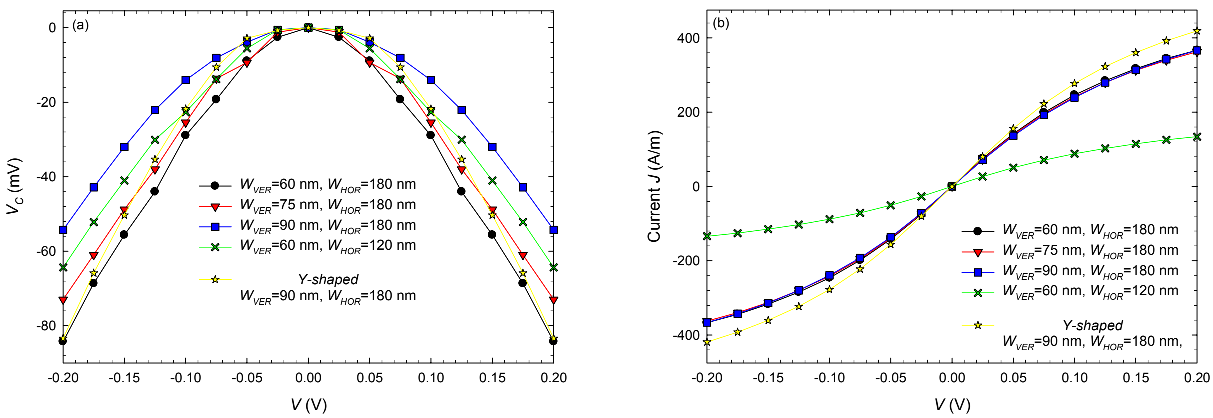

Figure 2. MC values of (a) bottom potential V_C and (b) current as a function of the push-pull bias calculated in T-shaped junctions with different W_{VER} and W_{HOR} and in a Y-shaped junction.

For the dynamic study of the TTJs, sinusoidal signals of 0.1 V of amplitude are applied to the left and right branches, while monitoring the value of V_C. The amplitude of its response informs about the capability of operating the TTJs as frequency doublers, while the average DC value of V_C provides the rectification capability. Both quantities are plotted in dB in figure 3 for the different TTJs studied (once subtracted the low frequency value). As a general feature, the cut-off for the amplitude of the output [figure 3(b)] appears at much lower frequencies than for the mean value [figure 3(a), with cut-off frequencies around 1 THz]. Different mechanisms are involved in the cut-off of both quantities. The DC value of V_C (used for rectification and thus detection) is mainly related to the electron horizontal transport, which is very fast. As a result, its cut-off is hardly influenced by the width of the vertical branch. On the other hand, the AC amplitude of V_C (and thus frequency doubling) is controlled by the penetration of carriers in the stem, so that its width (W_{VER}) clearly changes the cut-off frequency (higher frequencies for wider stems, in which carriers enter more easily). Since the electric field that forces electrons to enter/leave the vertical branch following the excitation signal is small, the characteristic time of such a process is much longer than the transit time associated to horizontal transport, so that the cut-off frequency for the amplitude of the output AC signal is much lower than in the case of the DC value, the difference being more significant the narrower the stem is. Nevertheless, wider stems provide less negative values of V_C at low frequency, as observed in figure 2(a). As a consequence, for an optimized response W_{VER} must be chosen depending on the required type of operation and frequency. On the other hand when reducing the width of the horizontal branch (W_{HOR}), a slight increase of the cut-off frequency is observed in both quantities; however, the matching to the typical 50 Ω lines would be worse due to the higher impedance of the TTJ. Concerning the shape, the Y geometry much improves the global performance of the device as a result of a stronger injection of carriers into the stem (having a more pronounced influence on the cut-off for frequency doubling). A better performance is expected when the angle of the junction is decreased.

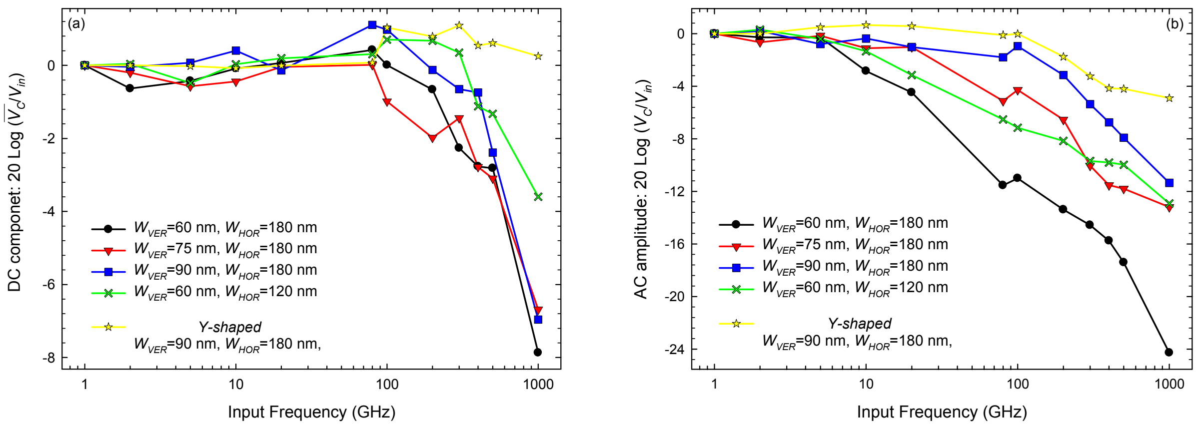

Figure 3. Average DC value and AC amplitude of V_C/V_{in} (in dB) as a function of the frequency of a sinusoidal push-pull input excitation of amplitude of V_{in}=0.1 V. For comparison, the low frequency value has been subtracted for each curve.

3. Experimental measurements

We report here experimental results illustrating the functionalities of TTJs previously analyzed by MC simulations. The geometry of a double Y-shaped junction has been defined by means of reactive ion etching on a typical InP-HEMT epilayer. Details of the fabrication process can be found in [4,7]. The complete frequency characterization of the structure between 3 and 40 GHz was presented in Ref. 8. In figure 4(a) it can be observed that the junction is still perfectly operative as detector at 94 GHz, with a measured sensitivity of 0.076 mV/μW (without DC bias). Concerning the devices acting as frequency doublers and phase detectors, we provide here new results obtained using a setup based on a Large Signal Network Analyzer (LSNA). After adequate calibration steps, the injected and reflected waves (phase and magnitude) at the input and output of the device are used to determine the currents and voltages in the frequency or time domain. In figure 4(b) an excellent frequency doubling for an input signal of 4 GHz can be observed: a quasi sinusoidal signal at 8 GHz is clearly obtained at the output. In order to check the possibility of phase detection, signals have been applied to the right and left branches with three different phase-shifts. The results of these measurements are shown in figure 4(c). They are in a very good agreement with the simulations. The main improvement with respect to previous works [4] is the optimization of the ohmic contacts and coplanar waveguide design in order to minimize extrinsic crosstalk capacitances without excessively increasing access resistances (their high impedance is one of the main problems of these ballistic nanodevices).

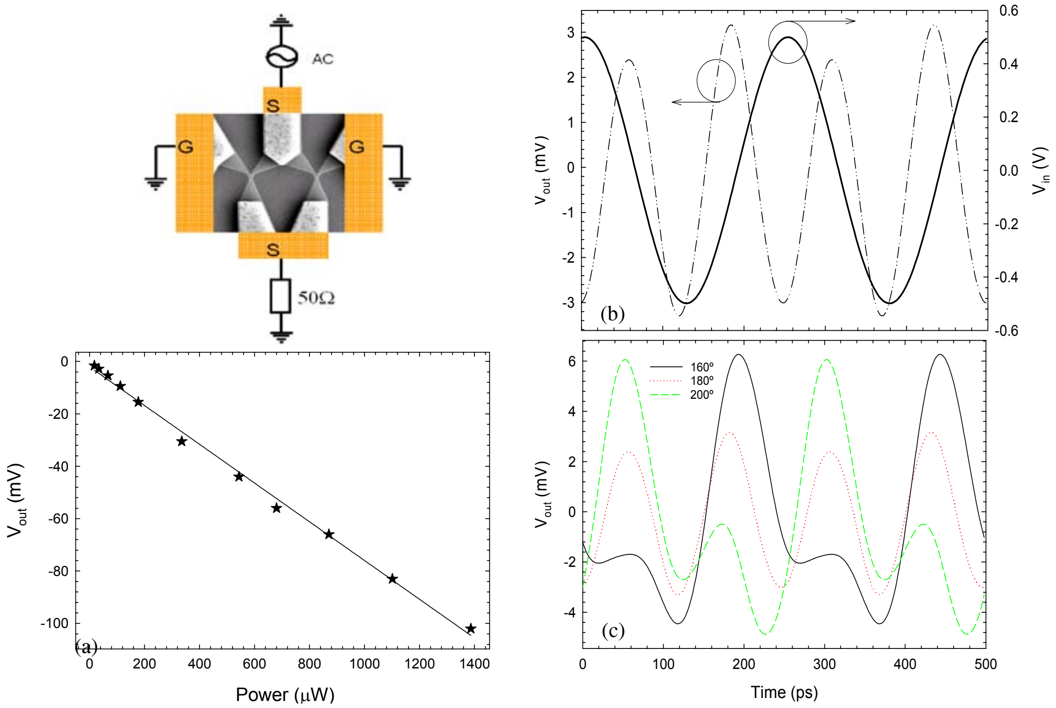

Figure 4. (a) V_C vs. microwave (94 GHz) power injected to the double Y-shaped junction shown above with V_{bias}=0. LSNA characterization at 4 GHz working as (b) frequency doubler with a -5dBm input signal and (c) phase detector (output for signals with different phase-shift between inputs).

4. Conclusions

By using MC simulations, the influence of the shape and branch sizes of TTJs on their dynamic behavior has been studied. Signal detection up to 94 GHz and frequency doubling and phase detection up to 4 GHz have been experimentally confirmed in a double Y-shaped junction.

This work has been partially supported by the Dirección General de Investigación (MEC) and FEDER (project TEC2007-61259/MIC and Acción Integrada HF2007-0014) and by the Consejería de Educación, Junta de Castilla y León (projects SA019A08 and GR270).

References

[1] Shorubalko I *et. al.* 2001 *Appl. Phys. Lett.* **79** 1384
[2] Mateos J *et. al.* 2003 *IEEE Trans. Electron Devices.* **50** 1897
[3] Sun J *et. al.* 2007 *Nanotechnology* **18** 195205
[4] Gardès C *et. al.* 2008 *Int. J. Nanotech.* **5** 796
[5] Mateos J *et. al.* 2003 *IEEE Trans. Electron Devices* **50** 1897
[6] Iñiguez-de-la-Torre I *et. al.* 2007 *Semicond. Sci. Technol.* **22** 663
[7] Iñiguez-de-la-Torre I *et. al.* 2009 *J. Appl. Phys.* **105** 094504
[8] Bednarz L *et. al.* 2006 *IEEE Trans Nanotech.* **5** 750