Ballistic devices based on T-Branch Junctions and Y-Branch Junctions on GaInAs/AlInAs heterostructures

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Abstract – **We present processes for building passive and active ballistic devices. A 2D Monte Carlo simulator was used to optimize these devices. We present also the study of the transition between ballistic and ohmic transport in T-Branch Junctions (TBJs) at room temperature by using DC characterization. Then we show experimental results for Y-Branch Junctions (YBJs) compared with Monte Carlo Simulations.**

I. INTRODUCTION

Because of the increasing amount of information to be transmitted, the development of digital/analog electronic devices for data processing at ultra-high bit rates and/or on high frequency carriers is a key issue. One way to reach this goal is to study and develop ballistic devices working at room temperature. In such a device, when the active area is smaller than the electronic mean free path, electrons are quite not scattered and are only diffused by walls of the device. The electronic transport becomes ballistic and leads to attractive behaviour.

The first step was to develop the technological processes to build our devices. These processes are based on GaInAs/AlInAs heterostructure on InP substrate. In section 2, we will detail processes based on HSQ resist developed for building passive and active devices. Passives devices include T-Branch Junctions (TBJs) and Y-Branch Junctions (YBJs). Active devices include TBJs and YBJs with schottky gates.

In section 3, we will present DC Characterization measurements of our passive devices at room temperature. We will first show TBJs DC characterization results. The objective of this part was to observe the transition between ballistic and ohmic transport. Then we experimentally demonstrated results predicted by Monte Carlo simulations on Y-Branch Junctions (YBJs), i.e. that the bottom branch potential in the central branch becomes more negative when the angle between the two others branches decrease.

II. TECHNOLOGICAL PROCESS

Our devices are based on GaInAs/AlInAs heterostructure on InP substrate (Figure 1). This heterostructure presents advantages of technological compatibility with HEMTs and good transport properties of the InGaAs channel at room temperature. An Indium content of 70% in the GaInAs channel is used in order to obtain high electron mobility and high mean free path.

As mean free path in such materials is still larger than 100 nm at room temperature [4], we should observe ballistic or quasi-ballistic behaviour for device with active area dimension around 100 nm.

Cap Layer	$Ga_{0.47}In_{0.53}As$	100 Å
Schottky	$Al_{0.48}In_{0.52}As$	150 Å
δ-doped	Si	$4\text{-}4{,}5.10^{12}$
Spacer	AlInAs NID	
Channel	$\mathbf{Ga_{0.3}In_{0.7}As}$	**150 Å**
Buffer	$Al_{0.48}In_{0.52}As$ NID	2000 Å
Substrate	InP SI	

Fig. 1. Cross Section of InAlAs/InGaAs structures on InP Substrate

A. *Passive Devices*

For the realization of passive ballistic devices, technological process is achieved as following: mesa etching to define the active region, ohmic contact formation and finally bonding pads. The important point of this process is the mesa step, because it defines the active region of ballistic devices. To design the mesa, we used a high resolution negative resist called HSQ (HydrogenSilsesQuioxane). The e-beam machine used is a LEICA EBPG5000+. The minimum resolution of this tool is 7 nm. The etching process used is Reactive Ion Etching (RIE, $CH_4/H_2/Ar$). This etch mixture has been chosen because the etching rate of InGaAs and InAlAs materials are very low (a few 10 nm/mn), what is fundamental for the control of the device dimensions. The HSQ resist is then removed by using buffered fluorhydric acid solution (NH_4F: HF). The Figure 2 shows a SEM picture of a device realized by RIE.

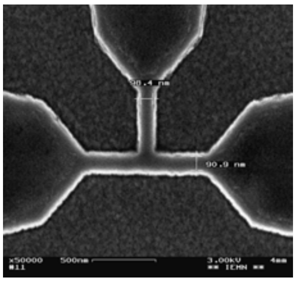

Fig. 2. SEM of T-Branch Junction by using RIE etching

By using RIE, the roughness of the devices is low and we can achieve devices dimensions closed to mask dimensions. Accuracy of the dimensions is indeed important for such small ballistic devices.

We have also experimentally determined that the depletion width at the interface between the air and the semiconductor is about 40 nm for each side.

Moreover the minimum device size defined as 2 times the sum of the depletion width W_d and the undercut should be 80 nm.

B. Devices with gates process, Monte Carlo optimization

In order to control the electronic flow inside the TBJ, Schottky gate is added on top of passive devices. The device showed here is a TBJ with a top gate (Figure 3).

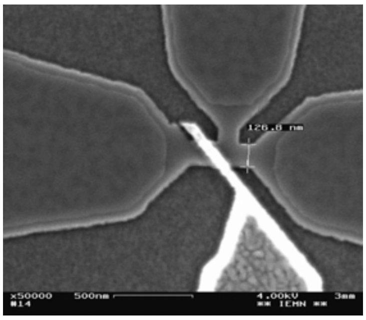

Fig. 3 SEM of T-Branch Junction with schottky gate

For these devices we defined mesas in two steps. First step is devoted to recess step (removing of the cap layer by using a SA (Succinic Acid)/H_2O_2 solution). The second step permits us to define the active part of the device by RIE. Then the schottky gate is defined by classical lift-off process. The resist used for the gate level is PMMA and metallization is Ti/Pt/Au.

The critical point is the positioning of the gates. As our TBJs are from 100 to 300 nm length, we achieved a high alignment precision for positioning gate. The mask design was optimized in order to reach best specifications of our ebeam equipment. By using this method, we achieved an alignment precision of about 25 nm, which is comparable to the best specifications of our equipment (2-3 times the spot size).

With such gated devices, we would like to build MUX/DEMUX devices. The first step is to realize a good switching gated TBJ. The potential applied to the gate contact V_G is used to deplete the right branch so that for low V_G the current is deflected into the bottom branch as described on **Figure 4** and when V_G is high, the current flows from right to left and bottom branches.

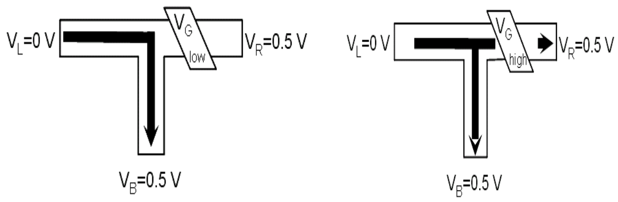

Fig. 4. Current flow into right and bottom branches when the Voltage gate Vg is low (left picture) and into the bottom branch when Vg is high (right picture) in ballistic transport.

For obtaining a good switching behaviour, when V_G is high, we have to minimize as much as possible the current in the bottom branch. To do that, we have performed 2D Monte Carlo simulations to modify the gated TBJ geometry (Figure 5).

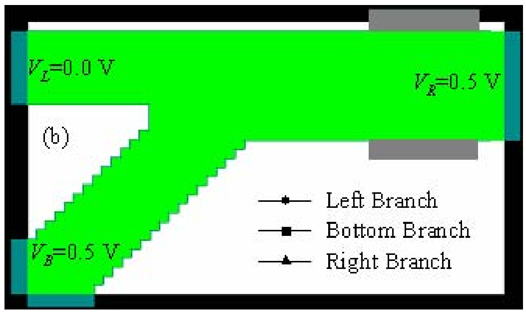

Fig. 5. Top view picture of the channel of a switching gated TBJ optimized by Monte Carlo simulation.

The values obtained for the current flowing through the right and bottom branches as a function of V_G for V_L=0 V and V_B=V_R=0.5 V are plotted in Figure 6. Voltages plotted for V_G in the figure were calculated considering a Schottky barrier height of 0.7 V.

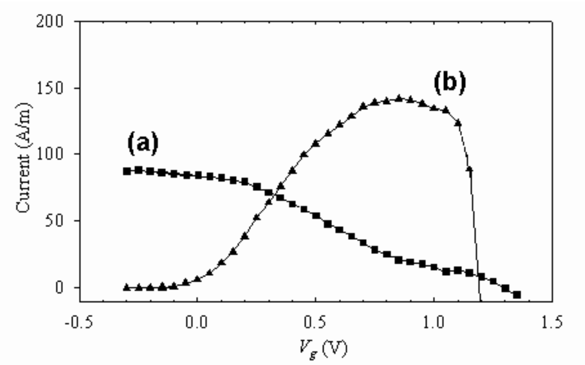

Fig. 6. Current flowing through the bottom branch (a) and the right branch (b) of the simulated gated TBJ versus gate voltage V_G.

So for low V_G, this device works adequately, deflecting almost completely the electron flow towards the bottom branch. When V_G is high, current in the bottom branch is not equal to zero because some electrons can go into this branch.

III. TBJS & YBJS DC CHARACTERIZATION AT T=300K

A. From ballistic to ohmic transport

Using DC Characterization, we observed the transition between ballistic and ohmic transport in TBJs. The objective was to evaluate dimensions we should design for building functional quasi-ballistic device at room temperature. We used the following method: In T-branch junctions, due to ballistic motion of electron, electrical potential V_{out} in the central branch of the TBJ follows a negative parabolic shape, when fixing the two other branches potential, one to $+V_{in}$ and the other one to $-V_{in}$ (Push-Pull Mode) . It was demonstrated by different ways [1-2], and also by experimental results at room temperature [3]. In the other case, if we go out of the ballistic transport, the device is ohmic and we observe a linear V_{out} behaviour. We present here the results of these measurements. For the smallest widths we observe a quasi-ballistic behaviour and when the width becomes larger, ballistic behaviour disappear (Figure 7). The best case is obtained for a branch width of 100 nm.

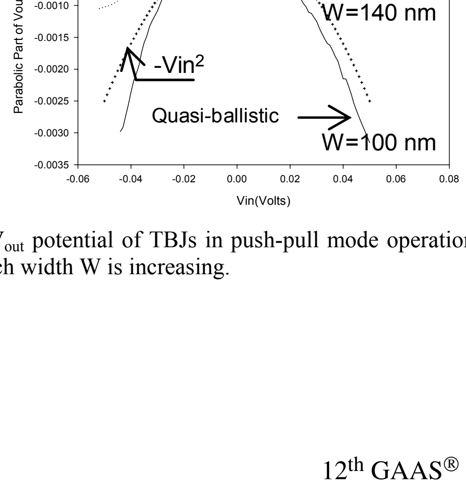

Fig. 7. V_{out} potential of TBJs in push-pull mode operation, when the branch width W is increasing.

B. YBJs, influence of the angle between two branches over the central branch potential

By using Monte Carlo simulations, it has been demonstrated that at room temperature [1], when the angle α between two branches decreases (figure 8), the central branch Vout potential becomes more negative [4]. This is due to the fact, that when α decreases, the injection of carriers in the central branch is more important and lead to a higher negative Vout potential. On Figure 7 we present experimental results on a YBJ of 250 nm branch length and 100 nm branch width (figure 9). The result obtained is in good agreement with the Monte Carlo simulations.

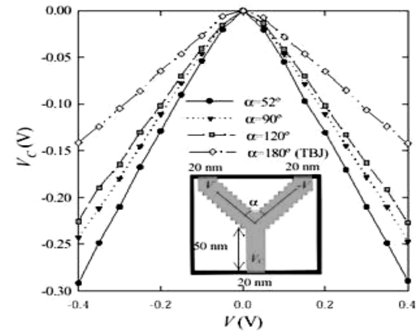

Fig. 8. Monte Carlo simulations of the Central Branch Potential in a YBJ in push-pull mode with variation of the angle α.

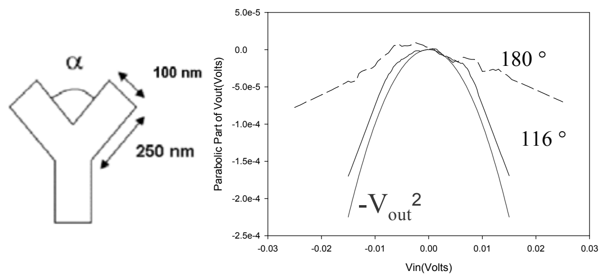

Fig. 9. YBJ central branch Vout potential vs Vin potential for α=116° and 180°

IV. CONCLUSION

We have presented in this paper our process technology to achieve the building of passive and active ballistic devices working at room temperature using a 2D Monte Carlo simulator for devices optimization. Characterizations of TBJ with gate are in progress and will be presented at the conference.

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REFERENCES

[1] Mateos J., Vasallo B.F., Pardo D.,Gonzalez T.,Galloo J.S., Roelens Y.,Bollaert S.,Cappy A., "Ballistic nanodevices for terahertz data processing: Monte Carlo simulations" *Nanotechnology*, 14(2003) 117-122

[2] Xu H.Q., "Electrical properties of three-terminal ballistic junctions", *Applied Physics Letters* , V.78,N°14 (2 april 2001)

[3] Xu H.Q., "A novel electrical property of three-terminal ballistic junctions and its applications in nanoelectronics", *Physica E*, 13 (2002) 942-945

[4] Mateos J., Vasallo B.F., Pardo D.,Gonzalez T., Galloo J.S., Bollaert S., Roelens Y., Cappy A., "Microscopic modelling of nonlinear transport in ballistic nanodevices", *IEEE Transactions on Electron Devices* 50, 1897-1905 (2003)