Ballistic nanodevices for high frequency applications

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Abstract: We report on the study of devices exploiting ballistic transport at room temperature by means of simulations and experimental results. Ballistic effects have been demonstrated at room temperature since a few years. This paper presents the work realised since 2001 on ballistic nanodevices at the Institut d'Electronique, Microélectronique et Nanotechnologie (IEMN). We will present the fabrication process and the characterisation of ballistic devices. We work on InGaAs-based devices optimised for ballistic transport, where the electron mean free path can reach around 130–160 nm at room temperature in channels with high indium content. We show that nanostructures around this size can be fabricated with the help of modern lithography techniques and are compatible with InP-HEMT technology. Devices under scope are Three-terminal Ballistic Junctions (TBJ) and their typical application is rectification. We have also characterised ballistic rectifiers up to 94 GHz. Measurements were realised on two TBJs integrated in

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parallel in a coplanar waveguide. We also show the frequency doubling characteristic of a single TBJ at 600 MHz.

Keywords: ballistic transport; Monte Carlo simulation; three-terminal ballistic junctions.

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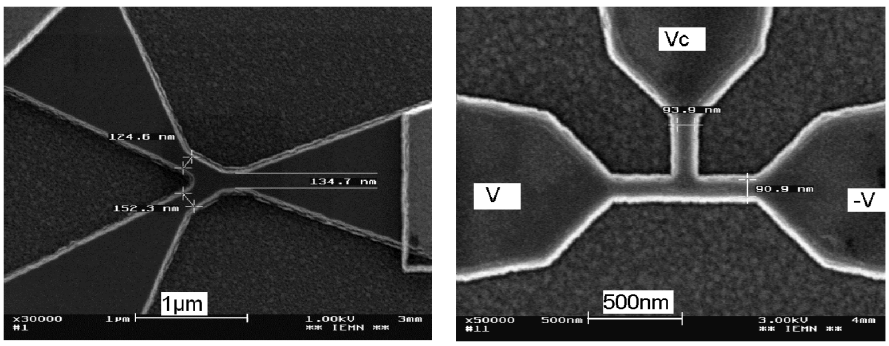
1 Introduction

This paper presents the work realised since 2001 on ballistic nanodevices at the Institut d'Electronique, Microélectronique et Nanotechnologie (IEMN) in Lille, France with the contribution of our collaborators within the European project Nanotera (University of Salamanca, USAL and Catholic University of Louvain, UCL). An important parameter to describe transport in semiconductors is the electron mean-free path, which is the average length between two electron scatterings. In diffusive devices, electrons experience scatterings with impurities, lattice defects or lattice vibrations (phonons). In a ballistic device, only elastic scatterings on boundaries are remaining. As a consequence, a ballistic device can be defined as a structure with size around or below the electron mean-free path so that most of electrons will transit without scattering. Ballistic effects in such device have been demonstrated at room temperature since 2000 [1–5] by authors involved in the European project Q-Switch. Hieke and Ulfward [2] have shown that at low voltage when biasing left and right branches of a three-terminal ballistic junctions (Y-branch device, see Figure 1) with opposite voltages V and $-V$ the floating potential V_c in the central stem is not equal to zero unlike what happens in a diffusive device, but has a negative value proportional to V^2. Xu [3], Shorubalko et al. [4] and Xu et al. [5] have shown this property on T-Branch junction (see Figure 1) and have described ballistic transport by Landauer-Büttiker formalism [6,7]. In our heterostructure, the electron mean free path is around 130–160 nm. Two geometries of ballistic devices are studied in this paper. We first report on T-branch junctions demonstrating the ballistic behaviour through DC characterisation. We also present Y-branch junctions [2,8,9], integrated in parallel in a coplanar waveguide topology that operate as rectifiers at high frequencies [10]. Finally, we present microwave measurements made with a large signal network analyser (LSNA) showing frequency doubler operation.

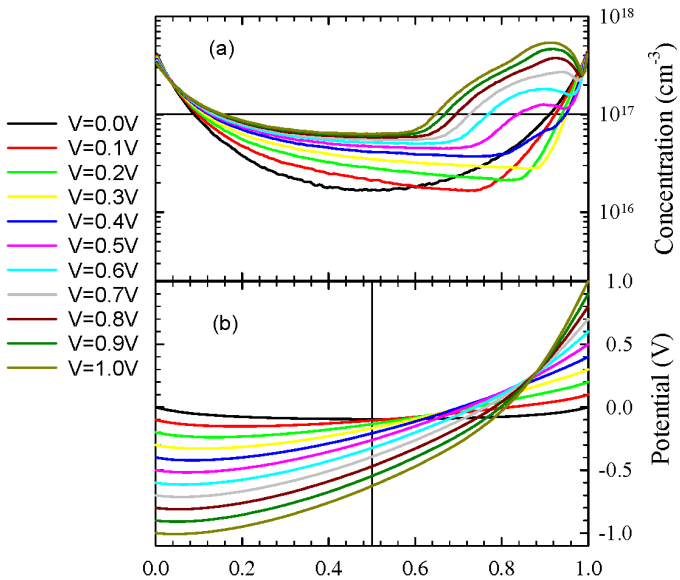
Figure 1 SEM images of an Y-branch junction and a T-branch junction



2 Monte Carlo simulations

The use of a Monte Carlo simulator developed by University of Salamanca [11–13], allows explaining the behaviour of TBJ not only at low bias and low temperature but also at high bias and room temperature. Monte Carlo allows to show that under low bias conditions, the electric potential and electron concentration profiles along the horizontal branch of a TBJ are not symmetric when biasing left and right contacts in push-pull mode ($V = V_l = -V_r$) (Figure 1). Space charge effects originated by the joint action of the lateral surface charge at the semiconductor-air interfaces and the charge injected by contacts lower the electric potential when moving away from the leads. This induces a depletion of the channel that explains the typical electric potential and concentration minima inside the structure (Figure 2). When biasing the TBJ the electron concentration becomes asymmetric, lower near the anode due to the velocity overshoot of quasi-ballistic electrons. The shift of the minimum of the potential profile towards the negative electrode when increasing the bias implies that the potential at the centre of the horizontal branch is more and more negative for larger V. For low bias, the negative voltage of the central stem is proportional to $-V^2$. When the TBJ is biased with higher voltage ($V > 0.25$ V i.e., more than 0.5 V applied between left and right branches), the central stem voltage is still negative but becomes proportional to $-V$. This linear behaviour is due to intervalley transfer. This forms a highly resistive accumulation domain near the anode, see Figure 2(a) [13]. This intervalley transfer, slowing down the electrons, is a potential limiting factor for high frequency applications. Thus, the bias should be kept below the onset of this scattering mechanism. Under these conditions Monte Carlo simulations have predicted the THz operation of nanodevices based on ballistic transport [12].

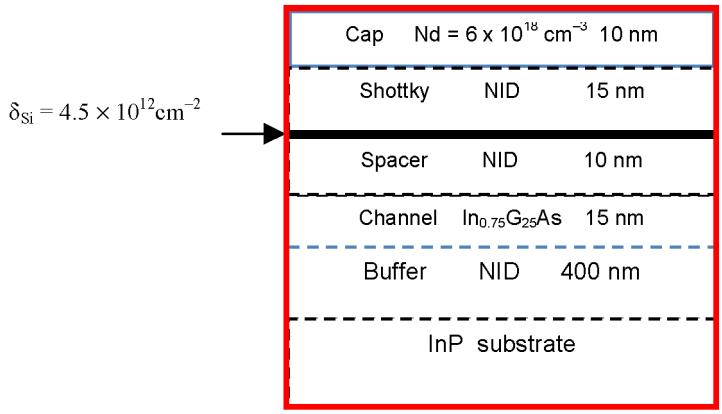
Figure 2 (a) Concentration and (b) electric potential profile along the horizontal branch of a 200 nm long TBJ with $V = V_l = -V_r$ (for colours see online version)



3 Layers structures and fabrication process

The epilayer structure has been realised by molecular beam epitaxy (MBE). It is comparable to the heterostructure used in InP-HEMT technology but optimised for ballistic transport (Figure 3). The cap layer thickness and doping have been fixed so that it is fully depleted, in order to avoid a parallel diffusive conduction. The δ-doping level and the spacer thickness are chosen in order to achieve the best compromise between high sheet electron density and low remote impurity scattering. The channel is a strained $In_{0.75}Ga_{0.25}As$ layer with high indium rate to get maximum mobility. Hall measurements of the wafer performed in the dark provide a mobility of 14,000 cm^2/Vs. and a sheet carrier density of 2.65×10^{12} cm^{-2} at room temperature (RT). At 77 K, as expected, there is a large improvement of mobility which is 74,000 cm^2/Vs. Besides the sheet-carrier density (2.60×10^{12} cm^{-2}) is about the same as the RT value which indicates that all free carriers are confined in the channel.

Figure 3 InGaAs/InAlAs heterostructure on InP subtrate used for ballistic device realisation



The geometry of the TBJ actually realised has been defined with a high resolution negative resist, Hydrogen SilsesQuioxane which is exposed by electron beam lithography with a Leica EBPG5000+. The acceleration voltage is 50 kV. Isolation is realised by dry etching with a $CH_4/H_2/Ar$ plasma. This solution has been preferred to wet etching because we have obtained lower shape roughness, a better control of undercut and no measurable degradation of transport by plasma. Then, the resist is removed with buffered oxide etchant (ammonium fluoride). A Ni-Ge-Au-Ni-Au metal sequence is deposited by evaporation and is annealed at 300°C with a N_2H_2 gas to form ohmic contacts. Finally, Ti-Au bonding pads are evaporated.

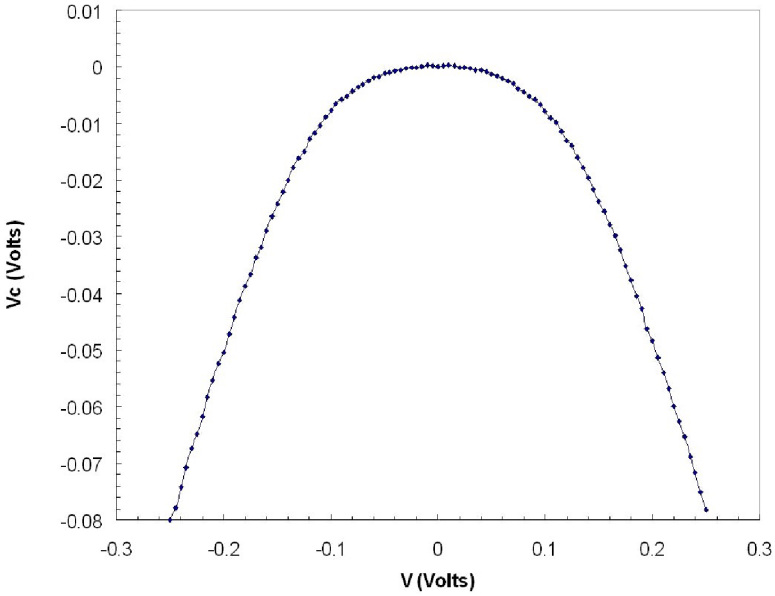
4 Experimental measurements

4.1 DC properties

The measurements when biasing TBJs in push-pull fashion (Figure 1) have been realised at RT, allowing the observation of the parabolic behaviour of V_c which characterises ballistic transport (Figure 4). This quadratic dependence of the potential measured in the

central branch $V_c = \alpha V^2$ (α the negative non-linearity coefficient, which depends on the geometry, V the value of the potential applied in push-pull mode to the left (V) and right ($-V$) branches of a TBJ) was observed on TBJs with central branch widths ranging from few tens of nanometres up to around 100 nm. The sample Figure 4 corresponds to a central branch width of 80 nm.

Figure 4 V_c output potential of TBJ in push-pull mode operation



4.2 Microwave properties

Monte Carlo simulations show that the intrinsic non-linear behaviour is expected to persist at very high frequencies [12] (up to THz range). Then, this non-linearity can be used for rectification and frequency multiplication. Basically, with a sinusoidal input voltage V (with pulsation ω), applied in push-pull to the left (V) and right branches ($-V$):

$$V = A\cos(\omega t) \tag{2}$$

the voltage in the central stem of the TBJ is expected to be:

$$V_c = 0.5\alpha[1 + \cos(2\omega t)]. \tag{3}$$

As shown by MC simulations, the intrinsic cut-off frequency of ballistic devices should be in the THz range. However, the relatively high impedance presented by such devices in the microwave range (from kΩ to few 10 kΩ) could be a limitation to a practical wide frequency band operation, even when combined with moderate capacitive coupling between reservoirs and cross talk capacitance between microwave accesses (e.g., 1 kΩ vs. 1 fF give a RC cut-off frequency of about 160 GHz. Even if this example is very trivial vs. real component, the actual values of parasitics in our devices are within this order of magnitude and illustrate where is the most critical issue with our devices).

As a consequence, rectifying effects and frequency doubler properties are expected to hold as long as parasitic capacitances do not have too much influence.

4.2.1 Y-junction as rectifiers

We present here some results concerning AC-DC converters [14–16]. We have fabricated double Y-branch junctions integrated in parallel in a coplanar waveguide so that the global resistance is decreased (Figure 5). An optimisation of the device design has been made, mainly on the design of microwave accesses in order to reduce also capacitances. The rectifying effect is demonstrated by looking at the DC voltage in the output stem as a function of the applied RF frequency with a microwave power. Those measurements were shown in [16]. Broad-band frequency characterisation between 3 GHz and 40 GHz have been realised at UCL [15]. Measurements at 94 GHz have been realised at IEMN. Figure 6, which plots the output dc voltage vs. the applied microwave power at 94 GHz, was not presented before. This figure shows a negative linear dependence of the output voltage vs. input power at 94 GHz. This negative quadratic dependence is a proof that $-V^2$ characteristic of TBJ, can be obtained up to this frequency. The best sensitivity that we got at 94 GHz is 0.076 mV/μW without a DC bias. This result is comparable to the sensitivity of 0.075 mV/μW obtained very recently with self-switching diodes (SSD) at 110 GHz [17]. If we make the comparison between our devices and nanostructures of around the same size, such as four-terminal ballistic rectifiers [18], there is a real improvement since their sensitivity is under 0.004 mV/μW at 50 GHz. Despite this improvement, the sensitivity of nanodevices is still far below those of classical devices like Schottky diode or heterostructure backward diode (e.g., more than 2 mV/μW at 110 GHz with zero-bias heterostructure backward diode [19]).

Figure 5 Scheme of double Y-branch junction operating as RF to DC rectifier

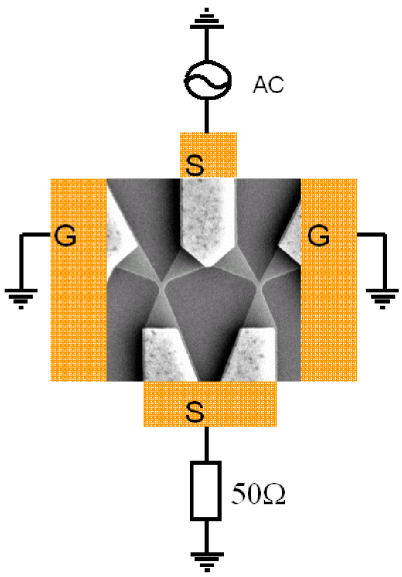
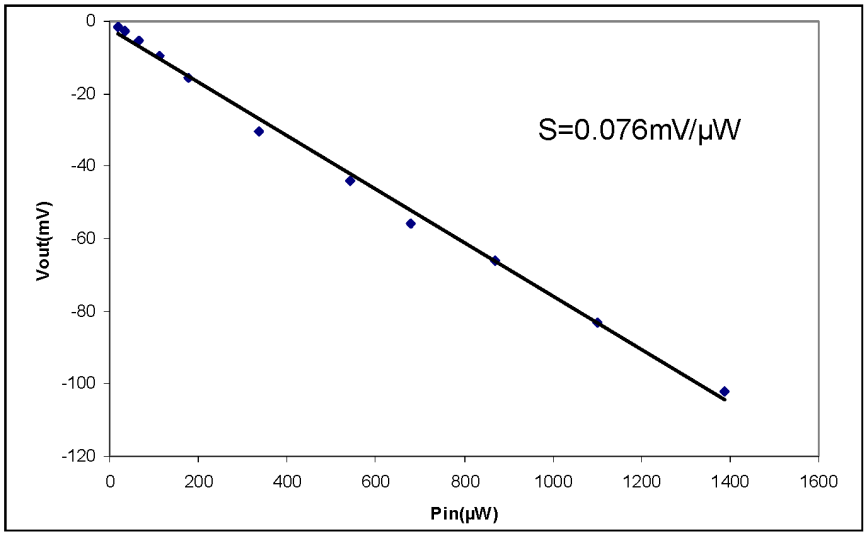


Figure 6 Ballistic behaviour of the rectifier at 94 GHz: detected DC voltage vs. microwave power



4.2.2 TBJ as frequency doubler

To our best knowledge, very few results were presented in the literature about this second aspect:

- Shorubalko et al. [20] have made time domain measurements up to 37 Hz on T-shaped junctions in association with lateral-FET used for amplification of the output signal. The output signal, observed with an oscilloscope, has a frequency of 74 Hz but is quite more complex than just the second harmonic (sinusoid) plus the DC offset expected for a simple TBJ. Furthermore, THz operation of this device is expected by the authors but quite difficult to extrapolate from 74 Hz measurements and not obvious with this device including a very simple 1D lateral-FET. To our best knowledge, the best field effect devices are HEMTs with a current gain cut-off frequency (f_T) of 562 GHz [21] and no better results have been provided since 2002.
- Lewen et al. [22] have made measurements on TBJs, using a balun for input signal (up to 1 GHz) and a spectrum analyser. Those measurements allow showing as expected a second harmonic but the fundamental mode, which should have been theoretically rejected, is higher than this harmonic even at 20 MHz. This behaviour was predicted by the authors from DC measurements and is probably due to the use of a TBJ which does not present a perfect V^2 bell-shape curve, as explained by the authors.

- The necessity of using an external balun limits the frequency band which can be used in Push-Pull experiments as such devices usually operate up to 2 GHz maximum. To avoid the problems of feeding the HF signal in Push-Pull mode Push-Fix setup can be used. In such a case one of the branches is grounded and the HF signal has to be fed only to one input branch. Worschech et al. [14] were the first to report on HF signal rectification and second harmonic generation in TBJ device at room temperature for input signals up to 10 GHz. Similarly to results of Lewen et al. the decrease of output power of second harmonic with frequency of input signal was observed. Furthermore, the authors report a drastic increase of the first harmonic (fundamental mode) detected with increasing frequency. Even if this characteristic is not shown by the authors, push-fix measurement does not allow rejecting fundamental mode.
- Sun et al. [23] in a very recent paper, show frequency mixing and phase detection functionalities of three-terminal ballistic junctions which, despite being related to the use of TBJ's non-linearity, are more advanced topics which obviously, do not address the simple frequency doubling behaviour. Furthermore, significant signal decay was seen by the authors in the MHz range.

We report here new results on TBJ acting as frequency doublers, obtained using a new measurement setup. Main parts of this setup are a Large Signal Network Analyser (LSNA), a High Impedance Probe (HIP Picoprobe model 35) and a second synthesiser realised with an Agilent Technologies E8257D PSG Analog Signal Generator. The LSNA permits non-linear measurements on two ports in the 0.6–20 GHz frequency range. LSNA gives access to both injected and reflected wave at the input and output of the device in the probes planes after dedicated calibration steps. Knowing these quantities, we are able to determine the currents and voltages in the frequency or time domain [24]. This solution has two main advantages:

- Use of a high impedance probe allows measuring precisely what is applied on both left and right branches of the devices without assumptions and TBJ disturbances.
- Measurement of both the magnitude and phase of the harmonics allows recalculating the waveform. In fact, this equipment allows obtaining similar informations at microwave frequencies than those obtained with an oscilloscope at low frequencies.

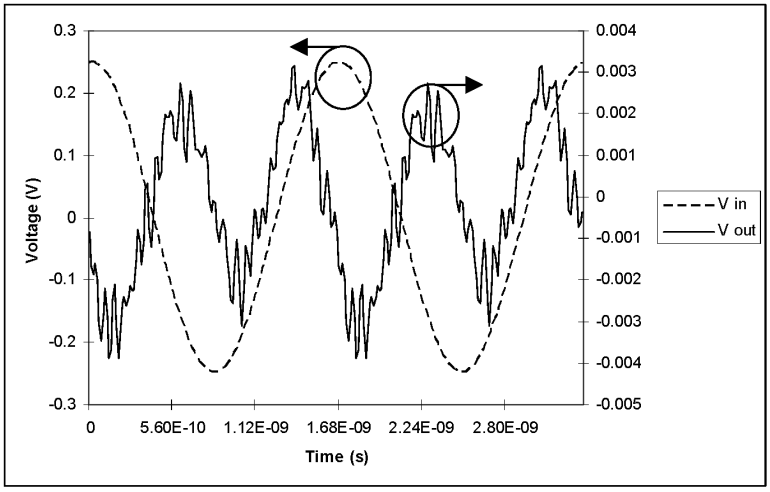
However, we have some limitations similar to those observed by Lewen et al. with a simple TBJ and a spectrum analyser:

- The central branch voltage of a TBJ is low, and then subjects to noise.
- The DC component is not measured. In our case, this is due to the high impedance probe which does not allow to measure the DC component.

In Figure 7, we present results of those experiments made on a TBJ (central branch width of 80 nm). We report measurement with a 600 MHz sinusoidal voltage applied to the left branch of the TBJ ($V_{in}(t)$), the same excitation being applied to the right branch voltage, but in opposite phase $-V_{in}(t)$ compared to the left branch. Achieving this push-pull condition is mandatory to observe fundamental mode rejection. The module was set to

0.25 V in order to avoid intervalley transfers. As expected by the simple theory (equation (3)) we obtain a sinusoidal shape with a frequency of 1.2 GHz which clearly illustrates that the highest voltage component is the second harmonic and that the fundamental mode is nearly rejected.

Figure 7 Characterisation with a LSNA of a TBJ operating as a frequency doubler with a 600 MHz input signal and an input power of –5 dBm. V_{in} is the potential applied to the left branch in the time domain. V_{out} is the output signal in the same time range



These results could be improved by giving careful attention to accesses design in order to reduce parasitics, particularly capacitances between contacts, which are an important limiting factor to reach high frequency data processing. Indeed, less work has been done on this point for TBJs, compared to the optimised YBJ rectifiers presented in this study.

5 Conclusion

In this report, we have presented the work that has been realised since 2001 on ballistic nanodevices at the IEMN with the contribution of our collaborators from the European Nanotera project. The initial results of this work were the fabrication of nanoscale TBJs and the experimental confirmation of the DC 'bell-shape' of the $V_c - V$ characteristic (previously measured by labs involved in European Q-SWITCH project). Then, the adaptation of a Monte Carlo simulator code for the study of TBJs allows to retrieve the typical $-V^2$ behaviour at low field but also to explain the change of slope at higher bias due to electron intervalley transfer. This Monte Carlo simulator predicts intrinsic THz operation of TBJs. We have also presented high frequency measurements proving two predicted properties: DC rectification and frequency doubling. For the DC rectification we have shown a measurement on optimised double YBJ, which demonstrates that $-V^2$ behaviour remains even at 94 GHz. For the frequency doubling part, we have presented a new measurement system well adapted for high frequency measurement of nanodevices and presented the first measurement showing a strong second harmonic at 1.2 GHz and a

rejection of fundamental mode (600 MHz) as theoretically expected. However, we have also shown that the prevalence of parasitics is a limiting factor for reaching high frequency performances in ballistic devices, especially the high intrinsic resistance and external capacitances. This can be extended to any nanodevice operating at high frequencies, including semiconductor nanowires or carbon nanotubes. As a consequence, the reduction of parasitic effects and a high level of parallelisation are required to improve the cut-off frequency. This point still needs optimisation in order to have a chance to compete with classical components.

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References

1 Hieke, K., Wesström, J.O., Forsberg, E. and Carlström, C.F. (2000) 'Ballistic transport at room temperature in deeply etched cross-junctions', *Semicond. Sci. Technol.*, Vol. 15, pp.272–276.

2 Hieke, K. and Ulfward, M. (2000) 'Nonlinear operation of the Y-branch switch: ballistic switching mode at room temperature', *Phys. Rev. B*, Vol. 62, pp.16727–16730.

3 Xu, H.Q. (2001) 'Electrical properties of three-terminal ballistic junctions', *Appl. Phys. Lett.*, Vol. 78, No. 14, pp.2064–2066.

4 Shorubalko, I., Xu, H.Q., Maximov, I., Omling, P., Samuelson, L. and Seifert, W. (2001) 'Nonlinear operation of GaInAs/InP-based three-terminal ballistic junctions', *Appl. Phys. Lett.*, Vol. 79, No. 9, pp.1384–1386.

5 Xu, H.Q., Shorubalko, I., Maximov, I., Seifert, W., Omling, P. and Samuelson, L. (2002) 'A novel device principle for nanoelectronics', *Mater. Sci. Eng., C*, Vol. 19, pp.417–420.

6 Landauer, R. (1957) 'Spatial variation of currents and fields due to localized scatterers in metallic conductors', *IBM J. Res. Dev.*, Vol. 1, pp.223–231.

7 Büttiker, M. (1986) 'Four-terminal phase-coherent conductance', *Phys. Rev. Lett.*, Vol. 57, pp.1761–1764.

8 Palm, T. and Thylen, L. (1992) 'Analysis of an electron-wave Y-branch switch', *Appl. Phys. Lett.*, Vol. 60, p.237.

9 Worschech L., Xu, H.Q., Forschel, A. and Samuelson, L. (2001) 'Bias-voltage-induced asymmetry in nanoelectronic Y-branches', *Appl. Phys. Lett.*, Vol. 79, No. 20, pp.3287–3289.

10 Bednarz, L., Rashmi, H.B., Farhi, G., Bayot, V., Huynen, I., Galloo, J-S., Roelens, Y., Bollaert, S. and Cappy, A. (2005) 'Low and room temperature studies of RF to DC rectifiers based on ballistic transport', *Microelectron. Eng.*, Vol. 81, Nos. 2–4, pp.194–200.

11 Mateos, J., Vasallo, B.G., Pardo, D., Gonzalez, T., Galloo, J.S., Bollaert, S., Roelens, Y. and Cappy, A. (2003) 'Microscopic modeling of nonlinear transport in ballistic nanodevices', *IEEE Trans. Electron. Devices*, Vol. 50, No. 9, pp.1897–1905.

12 Mateos, J., Vasallo, B.G., Pardo, D., González, T., Galloo, J.S., Roelens, Y., Bollaert, S. and Cappy, A. (2003) 'Ballistic nanodevices for terahertz data processing: Monte Carlo simulations', *Nanotechnology*, Vol. 14, pp.117–122.

13 Mateos, J., Vasallo, B.G., Pardo, D., González, T., Pichonat, E., Galloo, J.S., Bollaert, S., Roelens, Y. and Cappy, A. (2004) 'Nonlinear effects in T-branch junctions', *IEEE Electron. Device Lett*., Vol. 25, No. 5, pp.235–237.

14 Worschech, L., Schliemann, A., Reitzenstein, S., Hartmann, P. and Forchel, A. (2002) 'Microwave rectification in ballistic nanojunctions at room temperature', *Microelectron. Eng.*, Vol. 63, pp.217–221.

15 Bednarz, L., Rashmi, H.B., Farhi, G., Bayot, V. and Huynen, I. (2005) 'Broad-band frequency characterisation of double Y-branch nanojunction operating as room-temperature RF to DC rectifier' *IEEE Trans. Nanotechnol.*, Vol. 4, No. 5, pp.576–580.

16 Bednarz, L., Rashmi, H.B., Farhi, G., Bayot, V., Huynen, I., Galloo, J-S., Roelens, Y., Bollaert, S. and Cappy, A. (2005) 'Theoretical and experimental characterization of Y-branch nanojunction rectifier up to 94 GHz', *EuMW 2005*, 4–6 October, ISBN: 2-9600551-2-8.

17 Balocco, C., Song, A.M., Aberg, M., Forchel, A., González, T., Mateos, J., Maximov, I., Missous, M., Rezazadeh, A.A., Saijets, J., Samuelson, L., Wallin, D., Williams, K., Worshech, L. and Xu, H.Q. (2005) 'Microwave detection at 110 GHz by nanowires with broken symmetry', *Nano Lett.*, Vol. 5, No. 7, pp.1423–1427.

18 Song, A.M., Omling, P., Samuelson, L., Seifert, W., Shorubalko, I. and Zirath, H. (2001) 'Operation of InGaAs/InP-based ballistic rectifiers at room temperature and frequencies up to 50 GHz', *Jpn. J. Appl. Phys.*, Vol. 40, pp.L909–L911.

19 Meyers, R.G., Fay, P., Schulman, J.N., Thomas, S., Chow, D.H., Zinck, J., Boegeman, Y.K. and Deelman, P. (2004) 'Bias and temperature dependence of Sb-based heterostructure millimiter-wave detectors with improved sensitivity', *IEEE Electron Device Lett*., Vol. 25, No. 1, pp.4–6.

20 Shorubalko, I., Xu, H.Q., Maximov, I., Nilsson, D., Omling, P., Samuelson, L. and Seifert, W. (2002) 'A novel frequency-multiplication device based on three-terminal ballistic junction', *IEEE Electron Device Lett*., Vol. 23, No. 7, pp.377–379.

21 Yamashita, Y., Endoh, A., Shinohara, K., Hikosaka, K., Matsui, T., Hiyamizu, S. and Mimura, T. (2002) 'Pseudomorphic $In_{0.52}Al_{0.48}As/In_{0.7}Ga_{0.3}As$ HEMTs with an ultrahigh f_T of 562 GHz', *IEEE Electron Device Lett*., Vol. 23, No. 10, pp.573–575.

22 Lewen, R., Maximov, I., Shorubalko, I., Samuelson, L., Thylén, L. and Xu, H.Q. (2002) 'High frequency characterization of a GaInAs/InP electronic waveguide T-branch switch', *J. Appl. Phys.*, Vol. 91, No. 4, pp.2398–2402.

23 Sun, J., Wallin, D., Brusheim, P., Maximov, I., Wang, Z.G. and Xu, H.Q. (2007) 'Frequency mixing and phase detection functionalities of three-terminal ballistic junctions', *Nanotechnology*, Vol. 18, p.195205.

24 Verspecht, J. (2005) 'Large-signal network analysis', *IEEE Microwave Magazine*, Vol. 6, No. 4, pp.82–92.