Experimental study of transport in InAs Quantum Hot Electron Transistor

Thibaut Daoud, Guilhem Boissier, Jan Devenson, Alexei N. Baranov and Roland Teissier

Institut d’Electronique du Sud (UMR 5214, CNRS/UM2)
Université Montpellier 2, Place E. Bataillon, cc067
34095 Montpellier, France

roland.teissier@ies.univ-montp2.fr

Abstract. We study a Quantum Hot Electron Transistor, an original transistor made of InAs/AlSb heterostructures with high speed intrinsic transport. It is a unipolar vertical transport device, based on the concept of hot electron transistor. Devices using different heterostructure designs have been grown, processed and characterized. Both resonant and parasitic transport of electrons is studied by mean of the static output characteristics of the transistors. We demonstrated that a key parameter is the design and thickness of the collector barrier. For 15nm-thin barriers, we obtained static current gain of 5 associated to a base transit time of 140 fs.

1. Introduction

Shifting towards high indium content alloys, in order to benefit from the increase in electron mobility and high field velocity of these materials, is a general trend of high speed III-V microelectronics in recent years. Significantly improved performances, with frequency $f_{\text{t}}=760$ GHz, have been obtained with a Heterojunction Bipolar Transistor (HBT) using indium rich InGaAs material [1].

The work presented here aims to exploit the attractive properties of InAs to further extend the limits of vertical electron transport. Different attempts have been made to design HBTs with InAs or GaSb-based materials (also known as 6.1 Å material family) [2]. Our approach which is based on the concept of hot electron transistor [3] is radically different. The Quantum Hot Electron Transistor (QHET) that we developed [4] is a unipolar vertical transport device which uses a resonant transport through the exited states of a quantum well (QW).

We will present in this paper studies of electron transport in QHET through the analysis of static characterizations of devices made of different heterostructures. In particular, we will focus on the role of the collector barrier that controls base-collector leakage currents and also transit times through the base layer.

2. Device structure

2.1. Principle of operation

The QHET consists of a base layer made of a N-doped ~10nm thick InAs quantum well, an emitter and collector barrier made of graded InAs/AlSb superlattices, and a 100nm-thick InAs collector.
Figure 1. Conduction band profile of the InAs QHET under bias (in grey). The thick black lines represent the Fermi level in the three electrodes; the wavefunctions of relevant electron levels in the base layer are drawn; the light grey areas show schematically the electron minibands of the InAs/AlSb superlattices forming the emitter-base junction and the collector barrier. The main resonant and parasitic (thermal and tunnel leakages) transport channels are also indicated.

Majority electrons in the base are confined in the QW ground state thanks to the collector barrier, while minority hot electrons transit from emitter to collector through coherent transport via a QW excited state which is resonant with the emitter and collector barrier minibands (Fig.1).

Its two main advantages over HBTs are the low base sheet resistance accessible with moderate n-type doping levels (typically $10^{18} \text{ cm}^{-3}$) and very high speed electron transport in the InAs collector.

2.2. Fabrication

The structures were grown by molecular beam epitaxy on InAs substrates, using a Riber Compact 21 solid source machine equipped with As and Sb valved cracking cells. N-type InAs layers were doped with Silicon. Thanks to the expertise of IES in the growth of state of the art InAs/AlSb heterostructures for quantum cascade lasers [5], high quality structures were available for this work.

Large double mesa devices with 10x10 $\mu$m$^2$ emitter and 20x30$\mu$m$^2$ base have been fabricated, using standard UV lithography. Ohmic contacts on N-InAs were made of non alloyed Cr/Au metallization. In this device fabrication, a key technological step is the accurate contacting of the thin base. A high precision layer-by-layer etching process has been developed for that purpose [4].

3. Experimental study

3.1. Device characteristics

Devices using different heterostructure designs, have been tested. The resonant transport of electrons was studied by means of the static output characteristics of the transistors (Fig.2).
Because of the n-type of the base, leakage current from base to collector and voltage dynamic of the collector junction are critical issues. We report in the following on the experimental optimization of the collector barrier that controls collector parasitic currents. The main parasitic mechanisms are illustrated on Fig.1: majority electrons from the doped base layer can escape via thermal activation to the collector barrier miniband or tunnel through the collector barrier. In addition a breakdown of the bulk InAs layer in the collector junction can arise under high electric fields.

3.2. Thermal leakage
Thermally activated escape from the base strongly depends on the position of the collector barrier miniband (\( h \) parameter on Fig.1). We studied the base-collector junction characteristics for two structures, with \( h \) equal to 0.3 and 0.45eV respectively. The experimental curves are shown on Fig.3, indicating that thermal leakage becomes negligible with the higher barrier for \( V_{bc}<1.5V \). For reduced barrier height, the current is much higher and scales according to a simple activation energy model assuming thermal equilibrium.

3.3. Tunnel leakage
Another possible leakage current from the base is tunnelling to the collector. This mechanism, involving transfer from a localized state to a continuum of states, is non resonant, hence weakly dependent on the bias of the base-collector junction. In addition it must be proportional to the electron density in the base. We compared the leakage current at low bias of two structures with different base doping levels (Fig.4). Up to 0.8V, the current is very small and independent on doping level. It demonstrates that for the used barrier thickness of 18nm (6 QWs), tunnelling is negligible.
3.4. Bulk collector breakdown
At higher bias, the collector current increases rapidly. In order to understand the origin of this current and see the importance of breakdown in the bulk InAs of the collector junction, we studied a device in which we replaced InAs by a InAs/AlSb superlattice with the same composition as the collector barrier or, in other words, we used a 100nm-thick collector barrier. The comparison of this structure with the standard one (18 nm-thick barrier) is shown on Fig.5. For the device with thick barrier, the current is only due to thermal activation to the superlattice miniband. This thermal current must be of the same intensity for the thinner barriers whose miniband is at the same energy (same $E$). Hence the difference between the two characteristics comes from current generated in the InAs collector due to the onset of impact ionization in the high field region of this small bandgap material. We also studied a device with thinner barrier of 15nm (5 QWs). We observe a similar breakdown voltage, but no signs of increased parasitic tunnel current, thus confirming that this latter effect is still negligible.

3.5. Base transit time
The collector barrier thickness has also an important role on the electron transit time in the base, which is the time necessary to transfer electrons from the base exited state to the collector high field region. This time can be estimated from the static current gain which is, in a simple picture (see inset on Fig.2), the ratio of the electron relaxation time ($\tau_{rel}$) in the base QW to the base transit time ($\tau_t$). The value of $r_{rel}$ can be calculated to 0.7 ps, assuming that the main relaxation mechanism is LO-phonon emission. For the different devices presented in Fig. 5 with barrier widths of 100, 18 and 15 nm we measured current gains of 2, 3 and 5 respectively. This shows that transit time is significantly reduced when the collector barrier is thinned, with a value of $\tau_t=0.14$ ps for the 15 nm-thick barrier.

4. Conclusions
Through the experimental study of different structures, we explored the ability of the collector barrier superlattice to control the transport in InAs QHET. The height of the miniband controls the thermal leakage of electron from the base. We demonstrated that the tunnel current is negligible even for barriers as thin as 15 nm. The reduction of barrier thickness leads to an increase of the static current gain thanks to a reduction of base transit time. As a main conclusion this study demonstrated that thinner barriers are feasible and would be a way to further increase the gain.

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