Design of low leakage InGaAs/InAlAs pHEMTs for wide band (300MHz to 2GHz) LNAs

A. Bouloukou*, B.Boudjelida, A. Sobih, S. Boulay, J. Sly and M. Missous

School of Electronic and Electrical Engineering, University of Manchester
PO Box 88, Manchester M60 1QD, United Kingdom
e-mail: A.Bouloukou@manchester.ac.uk

This paper presents the design, fabrication and characterisation of InGaAs-InAlAs pHEMTs suitable for low frequency LNA designs. Transistors with variations in the supply layer thickness or Indium concentration are designed to provide for a range of transfer characteristics. Very low levels of leakage, of order of 0.2 μA/mm, are demonstrated by these pHEMTs, which enables the implementation of large-geometry, low-noise devices.

1. Introduction

The InGaAs-InAlAs pseudomorphic High Electron Mobility Transistor (pHEMT) occupies a prime position in the microwave and RF fields. Its excellent materials properties however are impeded by the presence of a relatively large leakage current that has hampered its use in applications requiring large gate periphery devices, such low frequency mobile communications or radio astronomy applications.

In the case of the Square Kilometre Array, the next generation radio telescope currently being internationally designed, low-noise operation is required at frequencies spanning the range 300MHz to 2GHz [1]. In this frequency range, matching the low noise amplifier (LNA) for wide band, low noise performance becomes a critical issue. To make an MMIC LNA insensitive to matching across the entire band requires the use of active devices that simultaneously exhibit a low minimum noise figure (NF_{min}) and a low noise resistance (R_n). Small gate length InGaAs/InAlAs pHEMTs are the best candidates for achieving very low NF_{min}, however the typically high leakage currents in this material system become even more pronounced as dimensions shrink and thus prevent the use of very large periphery devices, needed in reducing R_n.

The fabrication and performance of a novel family of InGaAs/InAlAs pHEMTs that have been engineered to provide exceptionally low levels of leakage currents [2] are presented here. Three pHEMTs have been designed with variations in the supply layer thickness or concentration to provide for a range of transfer characteristics. These are namely, XMBE#109 (nominal design), VMBE#1832 (wider band-gap supply) and VMBE#1841 (thinner supply). Comparative DC and RF results are used to discuss the suitability of each device as a potential candidate for low frequency, low noise amplifier designs.

2. Material growth and fabrication

All pHEMT structures under investigation were grown, in-house, using solid-source Molecular Beam Epitaxy (MBE) on two Oxford Instruments V90H and V100 systems. The VMBE prefix indicates samples grown in the V90H system while XMBE denotes growth in the V100. Considering the epitaxial layer structure from bottom to top, an un-doped InAlAs buffer layer is grown first, lattice matched to the

InP substrate providing the interface between the active layers and the substrate. The channel is formed in a highly strained, un-doped $In_{0.7}Ga_{0.3}As$ layer, grown well below the critical thickness for this composition (hc å 243 Å). The spacer is a lattice-matched, un-doped InAlAs layer of approximately 100 Å. The supply layer varies in terms of thickness and indium concentration among samples but has an identical level of ŭ-doping. Considering XMBE#109 as the baseline design with a lattice-matched InAlAs layer thickness of 300 Å, the variations amongst the other samples are as follows:

- VMBE#1832 incorporates a wider band gap supply layer based on strained $In_{0.26}Al_{0.74}As$ grown to approximately 280 Å. The wider band gap supply layer is aimed at providing a larger Schottky barrier to the channel, reducing the tunnelling induced gate leakage current and also improving the breakdown voltage.
- VMBE#1841 incorporates a 50% thinner (150 Å), lattice-matched, supply layer and is aimed at providing better charge control of the channel and increasing the transconductance of the device.

The cap of all samples is a thin (~50 Å), undoped, lattice-matched, InGaAs layer aimed at decreasing the electric field at the source-drain region. Low-resistivity Ohmic contacts are formed on this narrow band-gap layer by means of alloyed re-growth. The Hall mobilities and sheet carrier concentrations for all samples are given in table 1.

Sample	**XMBE#109**	**VMBE#1832**	**VMBE#1841**
Carrier conc., n_H (x10^{12} cm^{-2}) RT / 77K	1.7 / 2.1	1.45 / 1.7	1.2 / 1.65
Mobility, μ_H (cm^2/V.s) RT / 77K	12900 / 51200	10700 / 48100	13000 / 57800

Table 1: Hall effect results of the InGaAs/InAlAs pHEMTs.

Devices were fabricated by first defining isolated mesas by means of wet-etching down to the InAlAs buffer layer, using a non-selective etch (H_3PO_4:H_2O_2:H_2O). Source and drain Ohmic contacts were then formed through thermal evaporation and lift-off of AuGe/Au. The gate recess was subsequently formed in a self-aligned process, using the gate-level photoresist opening as a mask. A highly selective adipic acid etch [3] was used to remove the InGaAs cap layer and form the 50 Å gate recess. The gate electrode was deposited by thermal evaporation and lift-off of Ti/Au. Ti/Au probe pads were deposited to enable probing for on-wafer DC and RF measurements.

All transistors have a nominal gate length of 1εm and gate widths ranging from 200εm to 1.2mm. On-wafer DC and RF measurements were performed using an HP8510C vector network analyzer and an HP4142 parameter analyzer. Small-signal and noise parameters were extracted form the linear and non-linear models of the devices.

3. Results and discussion

3.1 DC characteristics

Devices on all three samples exhibit off-state breakdown voltages of over 14V (at I_G = 1mA/mm). The on-state leakage current densities are shown in figures 1(a) and 1(b). The maximum leakage, of ~13 εA/mm, is exhibited by VMBE#1841, as expected due to the increased tunnelling through the thinner (150 Å rather than 300

Å) supply layer. A very significant reduction in the level of on-state leakage is observed in VMBE#1832 where the maximum leakage is over an order of magnitude (0.2 εA/mm) less than in VMBE#1841 and more than 50% less than in XMBE#109. This level of leakage is most commonly associated with the more robust GaAs-based, rather than InP-based, devices and is due to the increase in the barrier height (*Φb*) provided by the wide band gap $In_{0.26}Al_{0.74}As$ and subsequent reduction of tunnelling as observed in table 2 and figure 1(c).

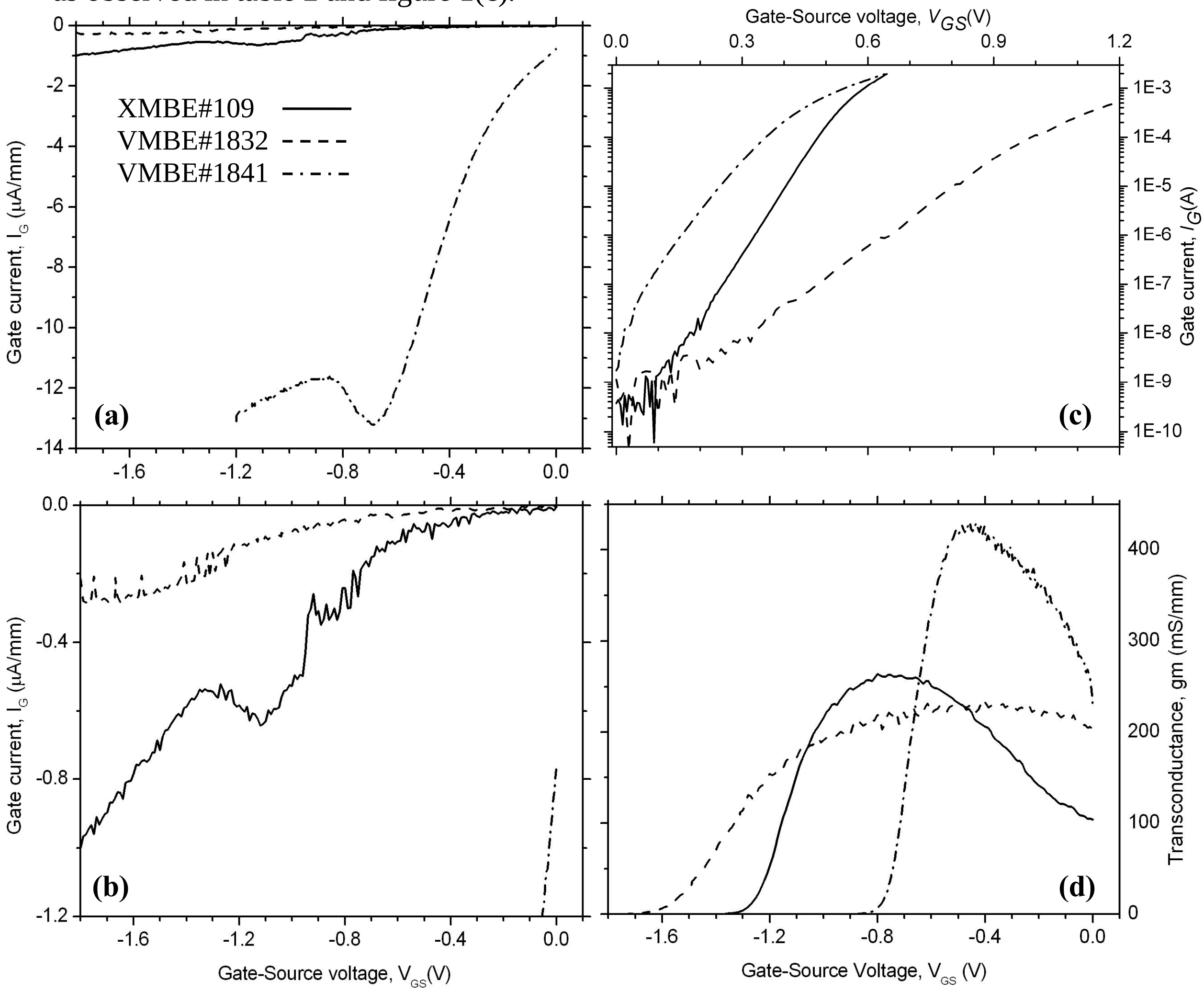

Figure 1: Typical, room temperature, on-state leakage current (a),(b), forward diode current (c) and transconductance (d) characteristics. (V_{DS} = 1V, L_g = 1μm, W_g = 200μm)

Comparing the observed leakage current levels with those reported for conventional InGaAs/InAlAs pHEMTs [4], the new devices exhibit much lower values. Particularly for samples XMBE#109 and VMBE#1832, minimal contribution to the on-state leakage due to tunnelling is observed. Such low levels of gate leakage indicate that it is possible to use large geometry devices, commonly employed in high-power applications, for low-noise operation, since for broadband amplification a low noise resistance (*Rn*) is necessary. A low *Rn* can only be achieved via the fabrication of very large periphery devices since it is proportional to *gm*. A low leakage device will permit this.

The transconductance characteristics, shown in figure 1(d), exhibit a sharply defined pinch-off. The higher maximum *gm* of VMBE#1841, compared to

VMBE#1832 and XMBE#109, is due to the better modulation efficiency of its shallower channel.

Sample	XMBE#109	VMBE#1832	VMBE#1841
Barrier height, *Φb* (eV)	0.61	0.61	0.46
Ideality factor, *n*	1.28	2.8	1.52
***n* x *Φb* (eV)**	0.78	1.71	0.7

Table 2: Typical, extracted Schottky diode parameters.

4. RF Characteristics

In addition to the DC characterisation of the devices, we have also analysed the microwave performance by taking measurement of small-signal S-parameters from 45 MHz to 50 GHz. The devices exhibit typical cut-off frequency and maximum frequency of oscillation ($f_T : f_{max}$) of (30 : 35) GHz, (30 : 31) GHz and (35 : 47) GHz for XMBE#109, VMBE#1832 and VMBE#1841 respectively. Based on equivalent circuit models, the noise characteristics of XMBE#109 yield Rn and NF_{min} of 5 ɋ and 0.5 dB respectively at 2 GHz. These results further support the case for using these novel devices for low frequency LNAs. A large geometry (800εm) device, built on XMBE#109, is currently used in the design and fabrication of a broadband monolithic LNA [5].

5. Conclusions

In conclusion, we have designed fabricated and characterised InGaAs-InAlAs pHEMTs suitable for low frequency LNAs. We have demonstrated that the InGaAs pHEMTs exhibit very low leakage levels with a maximum on-state leakage as low as 0.2 εA/mm, a level usually associated with GaAs-like devices.

The inherent low leakage of the structures enables large-geometry, low-noise devices to be implemented, which have been hitherto difficult to realise because of the inherent low breakdown voltages of conventional InGaAs-InAlAs pHEMTs. Devices with gate widths of 200 εm have been successfully demonstrated to operate up to frequencies of 35 GHz. The significant increase in transconductance that stems from the increase in gate area translates into a large decrease in the noise resistance of these devices, making them extremely promising as LNA components for implementation in broadband low frequency systems, such as the SKA receivers.

Acknowledgement

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