HEMT STRUCTURES AND TECHNOLOGY ON GAAS AND INP FOR POWER AMPLIFICATION IN MILLIMETRE WAVE RANGE.

D. Théron, Y. Cordier*, X. Wallart, S. Bollaert, M. Zaknoune, M. Boudrissa, B. Bonte, C. Gaquière, M. Rousseau, F. Dessenne, F. Mollot, A. Cappy, R. Fauquembergue and J.C. De Jaeger

Institut d'Électronique et de Micro-électronique du Nord,
UMR CNRS n° 8520, University of Lille Avenue Poincaré, B.P. 69
59652 Villeneuve d'Ascq, France, didier.theron@iemn.univ-lille1.fr

* CRHEA, rue Bernard Gregory
06560 Valbonne, France

ABSTRACT.

Today several HEMT structures are competing for power application in millimetre wave range. Some of them have been studied and realised in our laboratory. We will present the results and discuss advantages and potentialities.

PRESENT STATUS.

All HEMT structures on GaAs or InP use an InGaAs channel. The reason is that this material provides high electron mobility which increases with indium content. This parameter is therefore adjusted in order to enhance the frequency capability of the device. Higher indium content in InGaAs results in higher electron velocity but also lower breakdown field. That is why the achievement of high frequency and high power capability simultaneously is a challenge.

In the HEMT structure, the barrier layer is associated to the channel. It must provide large band gap, large conduction and valence band discontinuity with the channel and large Schottky barrier height. In addition this material has a free or passivated surface on each side of the gate after processing. Here low surface defect density must be achievable. Therefore low aluminium content material are preferable.

At 60 or 94 GHz, for the same output power GaAs PHEMTs integrated circuits (ICs) present lower gain and power added efficiency (PAE) as compared to InP based HEMT ICs [1,2,3,4] (Figure 1). This is due to the higher indium content in the channel of InP based HEMTs.

Improvement in device performance is still possible by changing the device structure and technology. In the past the indium composition was limited by the strain in the active layer induced by the lattice parameter of the substrate. Today metamorphic growth has removed this limitation so that a large range of indium composition can be used in HEMT structures varying from 0 to 100 % [5]. Several structures are challenging : GaInP/InGaAs on GaAs, AlInAs/InGaAs on GaAs or InP. Innovative semiconductors could be studied such as GaPSb, AlPSb or AlAsSb barrier layers [6,7].

Changing the barrier layer.

In PHEMT on GaAs, the AlGaAs barrier layer can be replaced by GaInP (Figure 2a). The growth of the GaInP/InGaAs interface must be accurately controlled in order to obtain a 2D gas with good electron density and mobility [8,9]. The device processing must also be changed. It benefits of the selective etching of GaAs over GaInP by H_2O_2 based solutions. But the ohmic contacts have to be redesigned because the presence of the GaInP barrier changes the diffusion process. Single recess structures have shown at 60 GHz a maximum output power of 560 mW/mm, 4.6 dB power gain and

22 % PAE (Figure 2b). However up to now we do not expect from this technology any improvement in electron velocity as compared to conventional PHEMT on GaAs [10].
In AlInAs / GaInAs HEMTs on InP, high aluminium content barrier layers are known to improve conduction and valence band discontinuities and Schottky barrier height. To our knowledge the best power devices have been obtained in the US with Al rich AlInAs [11] (480 mW/mm power density, 4.4 dB power gain, 30 % PAE).

Changing the channel.

Several ways are possible to improve the channel for power applications such as grading the channel or increasing the apparent band gap of the channel by reducing its thickness. In order to improve the breakdown of InP based HEMTs, composite channel HEMTs have been invented in Japan [12]. In this concept high energy electrons in the channel transfer into an InP subchannel where they have lower probability to create electron hole pairs and where they can move at high velocity. Several structures can be imagined depending on the location of the doping. Our investigations have concerned doped or undoped InP and delta doping of the AlInAs layer located under the channel (Figure 3). At 60 GHz we have demonstrated the best results with the structure of Figure 3b with 420 mW/mm and 44 % drain efficiency (Figure 4a). At 2 dB compression we have obtained 270 mW/mm power density, 3.3 dB power gain and 14 % PAE. We use pulsed measurements in order to evaluate the importance of the surface effects on the power performance [13]. They show that the excursion of the Id-Vds curve is correct on our devices except for a slight increase of the channel resistance à low drain voltage (Figure 4b).

Changing the technology.

A lot of various technologies are available for HEMT performance improvement such that alternate gate metal, new metal semiconductor interface treatment or surface passivation. Double recess has demonstrated better breakdown voltage and less surface effects [13,14]. It is therefore more suitable for power application. The cost is that the process is more complicated. We have studied different source drain configurations on the structure of Figure 3 which looks like a double recess due to the thin cap layer thickness. The gate was located at 0.5 µm from the source. Extending the source to drain distance from 1.3 to 3 µm has shown that the impact ionisation in the channel was reduced and that the on-state breakdown voltage was larger. Our best power results were obtained on the devices with 3 µm source drain distance.

FURTHER IMPROVEMENTS.

In principle, device structures grown on InP can be grown on GaAs using a metamorphic buffer. For instance composite channel HEMTs were recently demonstrated on GaAs [15]. Up to now we have obtained our best power densities or gain on structures using material compositions suitable for pseudomorphic growth either on GaAs or InP substrate. Moreover composite channel HEMTs on InP look very attractive for power application in millimetre wave range due to their high on-state breakdown voltage. Therefore most interesting device structures could be developed and studied on InP before using metamorphic material. This would make research easier because metamorphic buffers require a long growth time and careful optimisation of the surface roughness and lattice parameter relaxation.
Besides all these possibilities significant improvement in future device will come from gate length reduction. Gate length reduction will allow to increase frequency capability and pave the way towards future telecommunication systems working at 80 or 160 Gbits /s where cut-off frequencies as high as 300 or 600 GHz are required. For these technologies devices with 3 to 6 V breakdown

capability could be necessary for driving modulators. For that purpose simulation tools could help designing of these structures where short channel effects and non equilibrium could be important and electric fields very high.

ACKNOWLEDGEMENTS.

This work is financially supported by the French MOD. We thank all the engineers and technicians working on device technology and characterisation at IEMN for their contribution.

REFERENCES.

[1] O.S. Andy et al., "Design of High-Power, High-Efficiency 60-GHz MMIC's Using an Improved Nonlinear PHEMT Model", 1997 IEEE Journal of Solid State Circuits 32(9) pp. 1326-1333.
[2] P. Huang et al., "A 94 GHz monolithic high output power amplifier", 1997 IEEE MTT-S Digest pp. 1175-1178.
[3] Y.C. Chen et al., "A single chip 1-W InP HEMT V-band module" 1999 GaAs IC Symposium pp. 149-152.
[4] Y.C. Chen et al., "A 95-GHz InP HEMT MMIC Amplifier with 427-mW Power Output", 1998 IEEE Microwave and Guided Wave Letters 8(11) pp. 399-401.
[5] D. Xu et al., "Modulation-Doped Field-Effect Transistors with an 8-nm InGaAs/InAs/InGaAs Quantum Well.", 1999 IEEE Electron Device Lett. 20(3) pp. 109-112.
[6] M. Matloubian et al., "$Ga_{0.47}In_{0.53}As$/InP HEMTs with novel $GaP_{0.35}Sb_{0.65}$ Schottky Layers Grown by MOVPE.", 1998 Device Research Conference Charlottesville, Virginia, pp. 32-33.
[7] D.C. Dumka et al., "DC and RF Characteristics of Doped Multichannel $AlAs_{0.56}Sb_{0.44}/In_{0.53}Ga_{0.47}As$ Field Effect Transistors with Variable Gate-Lengths.", 2001 IEEE Electron Device Lett. 22(1) pp. 5-7.
[8] O. Dehaese et al., "As Surface Segregation during the Growth of GaInP on GaAs." 1997 Jpn. J. Appl. Phys. 36(11) pp. 6620-6624.
[9] O. Schuler et al., "Interface quality and electron transfer at the GaInP on GaAs heterojunction." 1998 J. Appl. Phys. 84(2) pp. 765-769.
[10] M. Zaknoune et al., "0.1 µm $Ga_{0.51}In_{0.49}P/In_{0.2}Ga_{0.8}As$ PHEMT grown by GSMBE with high DC and RF performances." 1999 Electronics Lett. 35(6) pp. 501-502.
[11] Pin Ho et al., "60 GHz power performnce of 0.1 µm gate-length InAlAs /InGaAs HEMTs.", 1994 Int. Conf. On Indium Phosphide and Related Materials pp. 411-413.
[12] T. Enoki et al., "Design and Characteristics of InGaAs/InP Composite-Channel HFET's." 1995 IEEE Trans. Electron Devices 42(8) pp. 1413-1418.
[13] J.C. Huang et al., "An AlGaAs/InGaAs Pseudomorphic High Electron Mobility Transistor With Imporved Breakdown Voltage for X- and Ku-Band Power Applications.", 1993 Trans. Electron Devices 41(5) pp. 752-759.
[14] C. Gaquière et al., "Breakdown Analysis of an Asymmetrical Double Recessed Power MESFETs." 1995 IEEE Trans. Electron Devices 42(2) pp. 209-214.
[15] C. Gässler et al., "Metamorphic HFETs on GaAs with InP-subchannels for device performance improvements.", 2000 IEEE Int. Electron Device Meeting, San Francisco, USA.

FIGURES.

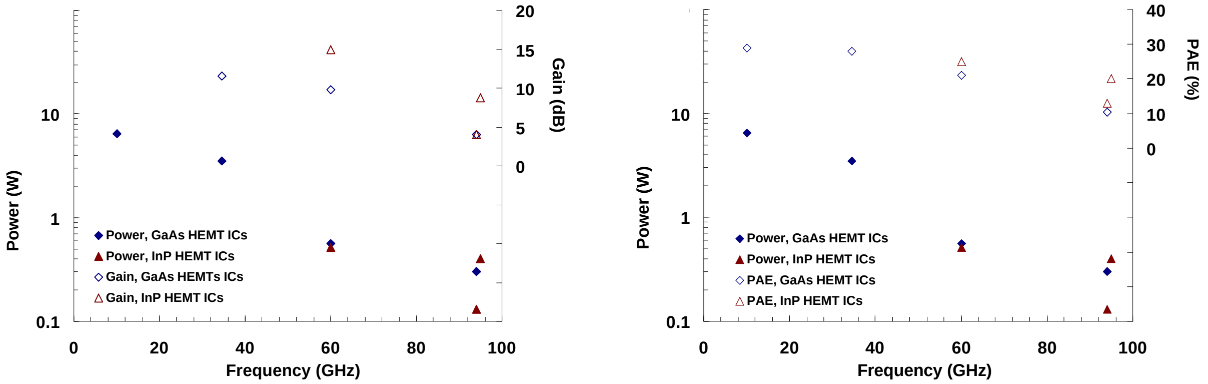
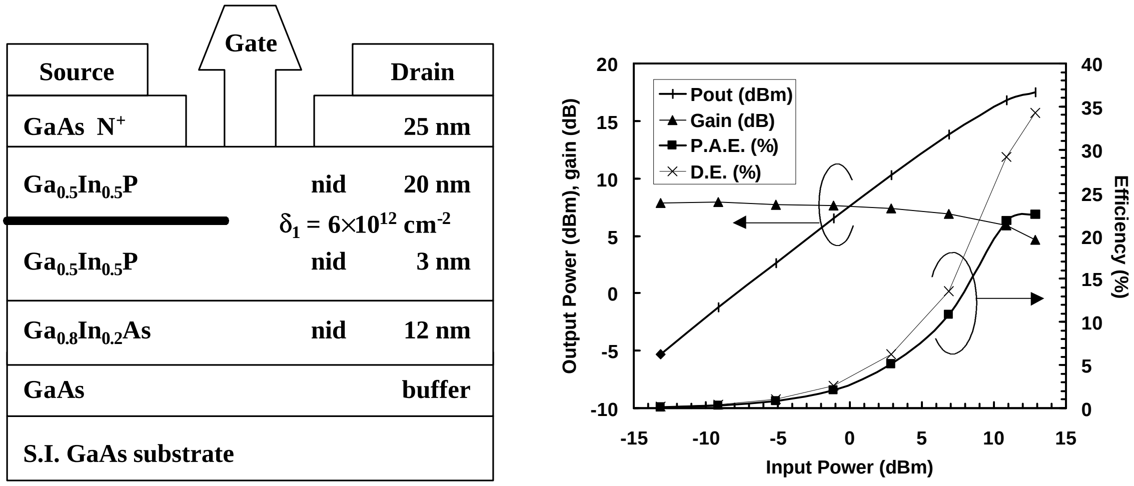
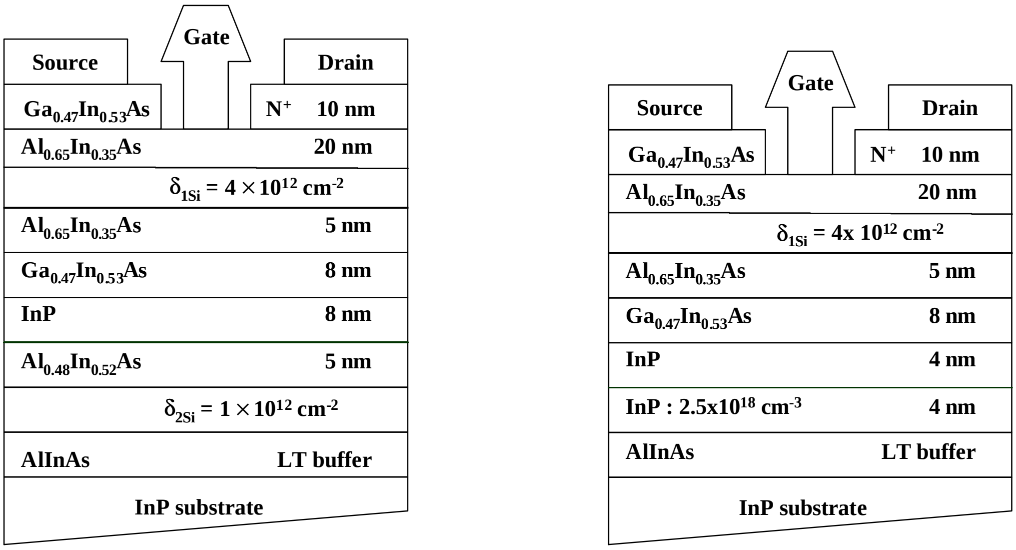


Figure 1 : Output power, gain and PAE of GaAs and InP based HEMT power amplifiers.



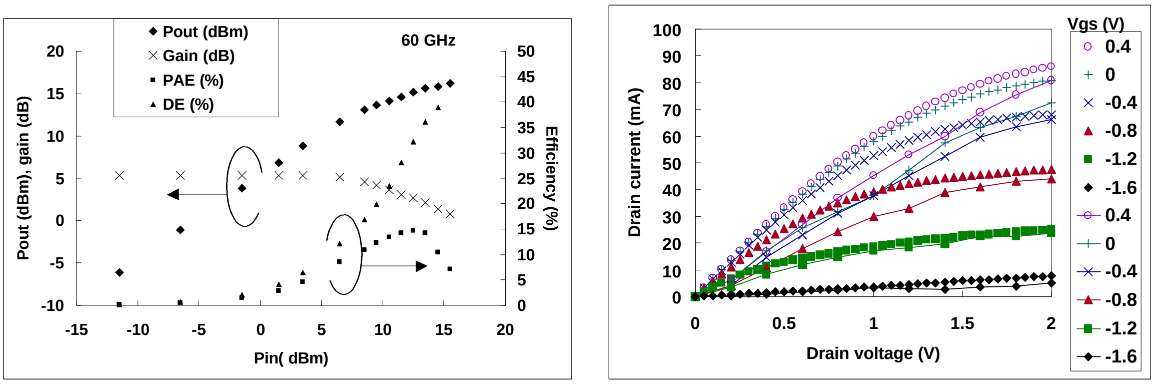
(a) *(b)*

Figure 2 : (a) Structure of a GaInP/InGaAs PHEMT on GaAs. (b) Output power, gain, power added efficiency and drain efficiency of the device at 60 GHz. L_g = 0.1 µm. Gate width 2´50 µm.



(a) *(b)*

Figure 3 : Different composite channel structures investigated for power applications at 60 GHz.



(a) *(b)*

Figure 4 : (a) Output power, gain and PAE of a composite channel HEMT on InP (structure of Figure 3b). L_g = 0.15 µm. Gate width 2´50 µm. (b) Comparison of DC (symbols alone) and pulsed measurements (symbols + lines). V_{ds0} = 2 V, V_{gs0} = -1.6 V.