Power Performance Capability of Metamorphic HEMT on GaAs Substrate

M. Zaknoune, Y. Cordier, S. Bollaert, D. Théron and Y. Crosnier

Institut d'Electronique et de Microélectronique du Nord
U.M.R.-C.N.R.S. 9929
Département Hyperfréquences et Semiconducteurs
Cité scientifique - Avenue Poincaré - B.P.69
59652 VILLENEUVE D'ASCQ CEDEX - FRANCE

ABSTRACT

An $In_{0.3}Al_{0.7}As/In_{0.3}Ga_{0.7}As$ *metamorphic power High Electron Mobility Transistor (HEMT) grown on GaAs has been developed. This structure with 30% indium content presents several advantages over PM-HEMT on GaAs and LM-HEMT on InP. A 0.15-µm gate length device with a single* δ *doping exhibits a current gain cut off frequency Ft value of 125 GHz at Vds = 1.5 V, an extrinsic transconductance of 650 mS/mm and a current density of 750 mA/mm associated to a high breakdown voltage of -13 V. Power measurements performed at 60 GHz demonstrate a maximum output power of 240 mW/mm with 6.4 dB power gain and a power added efficiency (PAE) of 25%. These are the first power results ever reported on any metamorphic HEMT.*

INTRODUCTION

Up to now, Double Heterostructure AlGaAs/InGaAs High Electron Mobility Transistor (HEMT) with 0.15 µm gate length and 50 µm gate width (1) are among the best devices suitable for power applications. They showed 0.84 W/mm, 37 % Power added efficiency (P.A.E.) and 5.9 dB power gain at 60 GHz, and 0.43 W/mm, 19 % P.A.E. and 3.2 dB power gain at 94 GHz. In pseudomorphic (PM) structures, the gain capability is limited by the maximum In content of about 25 %. Better electron transport properties could be achieved by using higher In content in the InGaAs layer. Therefore lattice matched AlInAs/GaInAs HEMTs on InP substrates have been developed by several groups in order to improve the frequency performance and the power density. However, the low Schottky barrier height in $Al_{0.48}In_{0.52}As$ compels to increase the Al content in the barrier layer up to 60 or 65 %. With this technology and a gate length of 0.15 µm, 0.4 W/mm with 3 dB power gain were obtained at 59 GHz (2). A better result has been obtained on a 0.1 µm gate length HEMT with 0.41 W/mm 8 dB power gain and 45 % P.A.E. With a double heterostructure pseudomorphic channel structure, the results are 0.48 W/mm, 4.4 dB power gain and 30 % P.A.E. (3). However the increase of the In content in the channel induces impact ionization and then premature breakdown and degradation of the output conductance. Therefore the investigation of unstrained metamorphic AlInAs/GaInAs structures on GaAs is presently a very hot field of interest for power applications in millimeter wave range. Thus, during these last years, there has been considerable interest in the development of metamorphic-based HEMTs (4). In this paper an $In_{0.3}Al_{0.7}As/In_{0.3}Ga_{0.7}As$ metamorphic power (HEMT) grown on GaAs is showed to have great potentialities for power applications at high frequency. This material composition offers several advantages over GaAs-based and InP-based HEMT. The relatively high (30%) indium content in the channel without strain results in higher electron mobility and saturated velocity. The high conduction band (0.7 eV) and valence band (0.3 eV) discontinuities improve the maximum current density and reduce the gate current related to hole generation in the channel. Furthermore the relatively high band gap of the InGaAs channel (~1 eV) limits impact ionization effects, and the high band gap of the InAlAs Schottky layer (~2 eV) improves the gate turn-on voltage.

MATERIAL GROWTH AND DEVICE FABRICATION

Metamorphic InAlAs/InGaAs HEMT layers (MM-HEMT) (fig.1) are grown by solid-source molecular beam epitaxy on two-inch (001) oriented semi-insulating GaAs substrates . The growth of continuously graded AlInAs metamorphic buffer layers on (100) GaAs substrate was achieved at low temperature to avoid island formation (Ts = 400°C) (5). Initial In content was set to 1% to minimize strain effect at the early stage of the growth of the layer and the thickness of buffer was 0.9 µm for 30% indium. The relaxation of the mismatch strain was measured using high resolution X-ray diffraction. At the top of the graded buffer, the relaxation rate is close to 85%. The relaxation of mismatch strain in the buffer layer generates a well defined surface morphology known as cross-hatch structure with main ridges parallel to the [01-1] direction. The surface roughness is measured by atomic force microscopy. A root mean square (RMS) surface roughness of 1.2 nm was determined toward [01-1] direction and a value of 3 nm toward [011]. However, the Hall effect measurements indicate a 2-DEG density of $3.5\text{x}10^{12}$ cm^{-2} with a mobility of 8500 $\text{cm}^2/\text{V.s}$ at room temperature and a 2-DEG density of $3.55\text{x}10^{12}$ cm^{-2} with a mobility of 23500 $\text{cm}^2/\text{V.s}$ at 77 K. These values are superior to those reported for a pseudomorphic channel on GaAs, confirming the superiority of the electron transport in unstrained material and the great interest of MM-HEMT over PM-HEMT for high frequency applications.

A 0.15-µm T-gate device was fabricated. Mesa isolation was achieved by wet chemical etching. The Ge/Au/Ni/Au ohmic contact metal was evaporated, followed by a rapid thermal annealing at 360°C for 10 seconds. A contact resistance of 0.25 Ω·mm was obtained. The T-gates were defined by electron beam lithography and a tri-layer resist scheme. The single recess etch was performed using a mixture of succinic acid and hydrogen peroxide with an $In_{0.3}Al_{0.7}As/In_{0.3}Ga_{0.7}As$ etch selectivity greater than 500. After recess etching, Ti/Pt/Au was deposited for the gates.

DEVICE CHARACTERIZATION

The 0.15-µm T-gate metamorphic HEMT's were characterized on-wafer for DC and RF performance. The output I-V characteristics are shown in figure 2. The MM-HEMTs have an maximum drain current of 750 mA/mm at Vgs of +0.4 V and an extrinsic transconductance of 660 mS/mm with a low output conductance of 30 mS/mm. The device also exhibits a excellent gate diode characteristic (figure 3) with a forward Schottky turn-on voltage of 0.9 V and a high gate breakdown voltage of -13 V measured at 1 mA/mm. The S-parameters of 100 µm wide MM-HEMTs were measured using on-wafer probing and a network analyzer (0.5 - 50 GHz). A current gain cutoff frequency Ft of 125 GHz and an Fmax of 230 GHz are extrapolated from the H_{21} and the Maximum Available Gain (MAG) for a 0.15-µm device biased at peak transconductance (figure 4). For comparison P. Win et *al* (6) had obtained with a similar structure a current density of 230 mA/mm, a transconductance of 700 mS/mm associated to a Ft of 45 GHz and a Fmax of 115 GHz for a gate length of 0.4 µm. In a recent work (7), we have been obtained for this composition a state of the art RF performance with a cut-off frequency of 160 GHz for a gate length of 0.1 µm.

Finally, the power performance was measured at 60 GHz on a $0.2\times150\text{-}\mu\text{m}^2$ gate length device biased at a Vds of 3 V and a Vgs of -0.8 V to operate in class A. The output power and power added efficiency versus input power are shown in figure 5. We obtain a maximum output power of 15.6 dBm (240mW/mm), a power added efficiency of 25% with a high power gain of 6.4 dB. These are the first power results ever reported for any metamorphic HEMT. In the table 1, we have reported some results to compare our performance. These are all PM-HEMTs on GaAs substrate with a double δ doping. We note that our device has a better power gain due to high Fmax even if the gate is only 0.2 µm. The power density of the devices presented in table 1 have above our. This is attributed to the double δ doping structure of these devices and to their technological optimization. Thus, we expect from the optimization of the structure associating the high breakdown voltage capability and the use of a double δ doped layer, a high power density with high power gain at 60 GHz.

CONCLUSION

In summary, the 30% indium mole fraction represents the best tradeoff between PM-HEMT on GaAs and LM-HEMT on InP for power amplification at high frequency because it allows to obtain simultaneously high frequency performance, high current density and a high breakdown voltage.

ACKNOWLEDGMENT

The authors would like to thanks the French ministry of defense for the financial support.

REFERENCES

(1) M.Y. Kao, P.M. Smith, P. Ho, P.C. Chao, K.H.G. Duh, A.A. Jabra et J.M. Ballingall, " Very high power added efficiency and low noise 0.15 µm gate length pseudomorphic HEMT's " IEEE Electron Device Letters, vol.10, n°12, pp.580-582, 1989.

(2) M. Matloubian, L.M. Jelloian, A.S. Brown, L.D. Nguyen, L.E. Larson, M.J. Delaney, M.A. Thompson, R.A. Rhodes and J.E. Pence, " V band high efficiency high power AlInAs/GaInAs/InP HEMT's " IEEE Transactions on Microwave Theory and Technique, vol.41, n°12, pp.2206-2209, 1993.

(3) P. Ho, P.M. Smith, K.C. Hwang, S.C. Wang, M.Y. Kao, P.C. Chao et S.M.J. Liu, " 60 GHz power performance of 0.1 µm gate-length InAlAs/InAlAs HEMTs " Proc. of the Int. Conf. on Indium Phosphide and Related Materials, pp. 411-413, 1994.

(4) M. Chertouk, H. Heiss, D. Xu, S. Krauss, W. Klein, G. Bohm, G. Trankle, and G. Weimann, "Metamorphic InAlAs/InGaAs HEMT's on GaAs substrates with a novel composite channels design," IEEE Electron Device Letters., vol. 17, pp.273-275, 1996.

(5) Y. Cordier, Y. Druelle, S. Bollaert, A. Cappy, Strudel, J. diPersio and D. Ferré, "MBE grown AlInAs/GaInAs lattice mismatched layers for HEMT application on GaAs substrate," Electronic Materials Conference, June 1997.

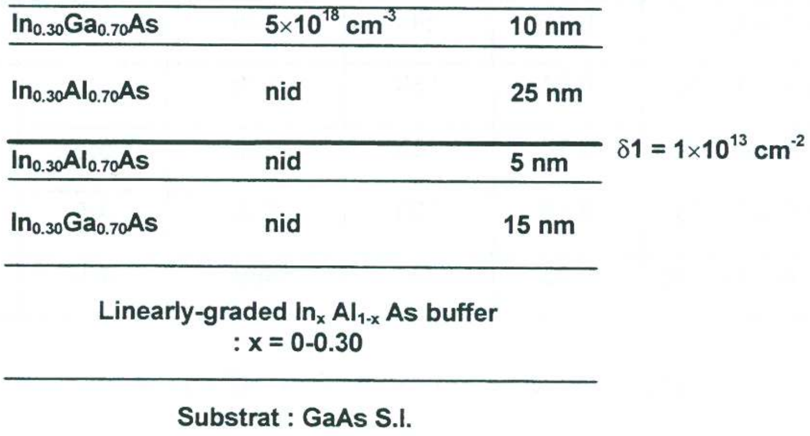
(6) P. Win, Y. Druelle, P. Legry, S. Lepilliet, A. Cappy, Y. Cordier, and J. Favre, "Microwave performance of 0.4 µm gate metamorphic $In_{0.29}Al_{0.71}As/In_{0.3}Ga_{0.7}As$ HEMT on GaAs substrate," Electron Letters., vol. 29, pp. 169-170, 1993.

(7) M. Zaknoune, Y. Cordier, S. Bollaert, Y. Druelle, D. Théron and Y. Crosnier, " High performance metamorphic $In_{0.32}Al_{0.68}As/In_{0.33}Ga_{0.67}As$ HEMT's on GaAs substrate with an inverse step InAlAs metamorphic buffer ", Device Research Conference, June 1998.

(8) P.M. Smith, P.C Chao, L. K. Lester, R. P. Smith, Lee, Ferguson, A. Jabra, J M. Ballingall, K. H. G. Duh, " InGaAs pseudomorphic HEMTs for millimeter wave power applications " IEEE Transactions on Microwave Theory and Technique Digest., pp.927-930, 1988.

(9) R. Lai, Wojtowicz, M. Chen, M. Biedenbender, H.C. Yen, D. C. Streit, K. L. Tan, P. H. Liu, " High power 0.15 µm V band pseudomorphic InGaAs-AlGaAs-GaAs HEMT ", IEEE Microwave and Guided Wave Letters., vol.3, n°10, pp.363-365, 1993.

(10) K. L. Tan, Dwight. C. Streit, R. M. Dia, Shing. K. Wang, A.C. Han, P. D. Chow, Tien. Q. Trinh, P. H. Liu, J. R. Velebir, H. C. Yen," High power V band pseudomorphic InGaAs HEMT ", IEEE Electron Device Letters., vol.12, n°5, pp.213-214, 1991.



$In_{0.30}Ga_{0.70}As$	5×10^{18} cm^{-3}	10 nm
$In_{0.30}Al_{0.70}As$	nid	25 nm
$In_{0.30}Al_{0.70}As$	nid	5 nm
$In_{0.30}Ga_{0.70}As$	nid	15 nm

$\delta1 = 1\times10^{13}$ cm^{-2}

Linearly-graded $In_x Al_{1-x} As$ buffer
: x = 0-0.30

Substrat : GaAs S.I.

Fig. 1. Schematic cross section of MM-HEMT on GaAs substrate.

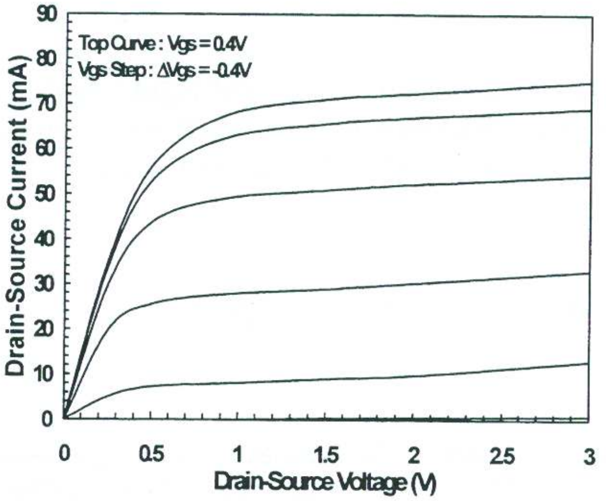


Fig. 2 : DC I-V characteristics of a 0.15×100-µm MM-HEMT.

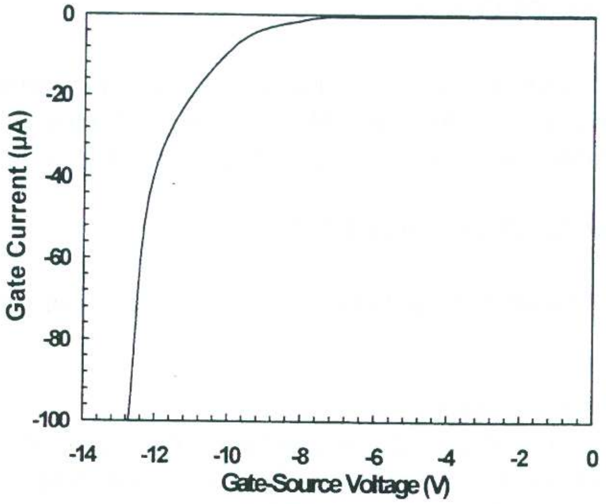


Fig. 3 : Gate diode characteristic of a 0.15×100-µm MM-HEMT.

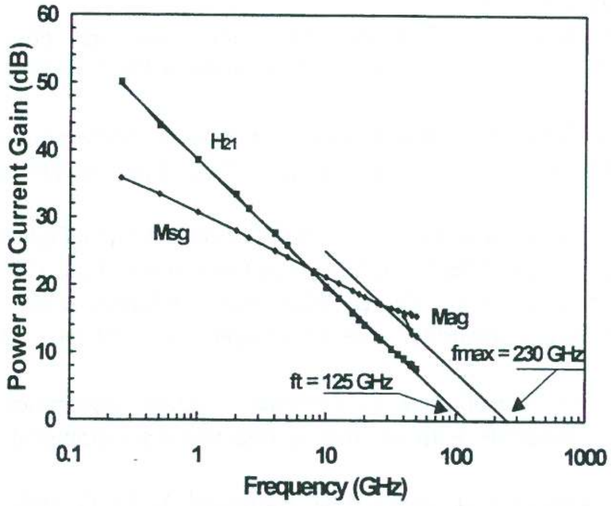


Fig. 4 : Power gain MAG MSG and current gain H_{21} against frequency for 0.15-µm MM-HEMT at Vds = 1.5 V, Vgs = -0.8 V.

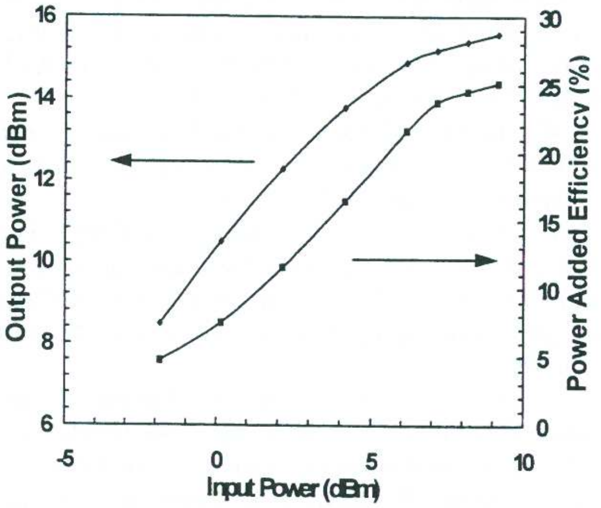


Fig. 5 : Output power and PAE versus input power at 60 GHz of a 0.2×150-µm MM-HEMT.

DEVICES	Lg (µm)	W (µm)	Ps (mW/mm)	Gain (dB)	PAE (%)
PHEMT on GaAs (1)	0.15	50	840	5.9	37
PHEMT on GaAs (8)	0.25	150	670	3	22
PHEMT on GaAs (9)	0.15	320	600	5.3	31
PHEMT on GaAs (9)	0.15	400	550	4.5	25.4
PHEMT on GaAs (10)	0.25	400	460	4.6	25

Table 1 : Power performances of PM-HEMTs at 60 GHz.