A HIGH PERFORMANCE, HIGH YIELD, DRY-ETCHED, PSEUDOMORPHIC HEMT FOR W-BAND USE

N.I. Cameron, M.R.S. Taylor, H. McLelland,
M. Holland, I.G. Thayne, K. Elgaid and S.P. Beaumont

Nanoelectronics Research Centre, Dept. of Electronics and Electrical Engineering,
University of Glasgow, Glasgow, Scotland

ABSTRACT

A GaAs pseudomorphic HEMT process has been optimised for high performance and yield at w-band. Several key nano-fabrication techniques are explored for performance, manufacturability and process sensitivity. The molecuar beam epitaxially grown pHEMT layer is optimised for reduced short channel effects, high transconductance (690 mS/mm) and reliability. Electron-beam lithography produces ultra short T-gates with high reproducibility. Selective reactive ion etching enables both the depth and width of the gate recess to be accurately controlled. 0.2 µm pHEMTs with two 50 µm gate fingers exhibit average values for f_T and f_{max} of 121 and 157 GHz with low standard deviations of 4.6 and 2.9 GHz respectively.

INTRODUCTION

W-band MMICs have been reported for both GaAs pHEMT technology [1] and InP HEMT technology [2]. While InP HEMTs offer superior small signal high frequency performance [3], pHEMTs based on GaAs substrates have advantages of wafer size, cost, process maturity and superior power performance at mm-wave frequencies. Issues of manufacturability and process sensitivity remain to be addressed however, if w-band MMICs based on GaAs pHEMTs are to find widespread application. In this paper we report the application of key nano-technologies to maximise the high frequency performance, yield and reliability of GaAs pHEMTs. The fabrication techniques we use are Molecular Beam Epitaxy (MBE), Electron Beam Lithography (EBL) and Selective Reactive Ion Etching (SRIE).

LAYER STRUCTURE OPTIMISATION

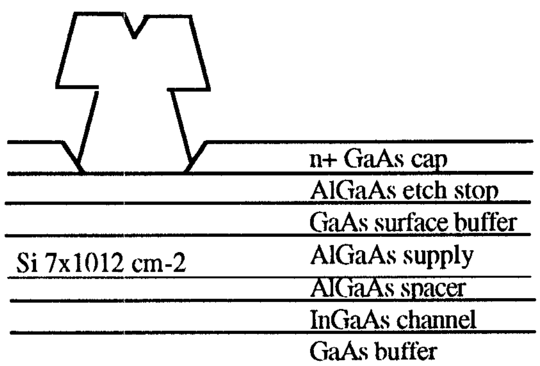

Figure 1. pHEMT Layer Structure.

The pHEMT layer, grown by MBE and shown in figure 1, was optimised for reduced short channel effects, high rf performance, reliability and yield. Because an etch stop and SRIE gate recess are used the depth of the channel below the gate is predetermined during growth and must be carefully designed into the structure prior to fabrication. Two layers, A and B, were grown with channel depths of 315 and 215 Å respectively. To enhance the reliability of the pHEMT we introduced an AlGaAs etch stop and GaAs surface buffer layer under the gate to prevent deep oxidation or corrosion of the AlGAs supply layer. After removal of the GaAs cap by SRIE we measured a sheet electron density of 2.5×10^{12} cm^{-2} and Hall mobility of 4860 cm^2/Vs at room temperature in the channel of layer B.

FABRICATION

pHEMTs with gate length ranging from 120 to 320 nm and gate widths from 50 to 200 µm,

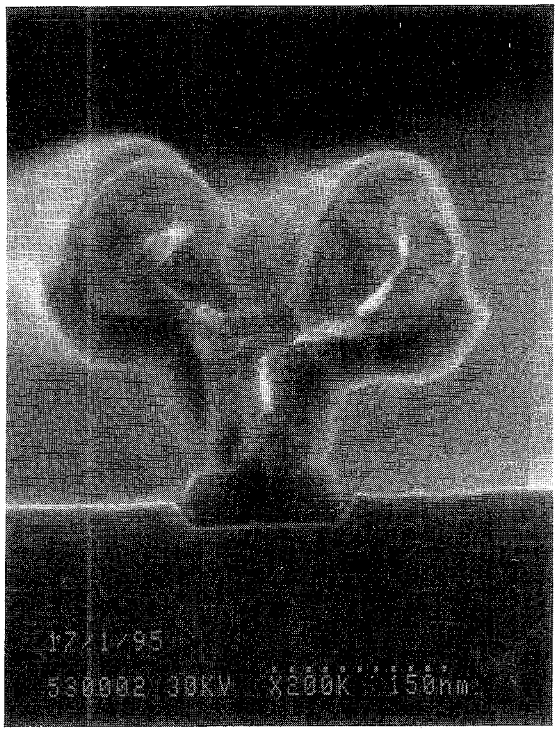

Fig. 2. SEM cross section of a 0.15 μm pHEMT

having a two finger π gate layout embedded in a coplanar waveguide structure were fabricated. All levels of lithography were written by EBL using a Leica-Cambridge EBPG-5HR or "Beamwriter". Tri-layer PMMA / P(MAA-MMA) / PMMA was used to form the T-profile gates. The gate recess was etched using SRIE with a selectivity between GaAs and AlGaAs of greater than 4000 to 1 [4,5]. An SEM cross section of a completed pHEMT having a gate length of 0.15 μm is shown in figure 2. No degradation of the electrical properties of the pHEMT layer, low frequency noise spectra [6], 2-26 GHz noise parameters or high frequency performance of devices has yet been observed due to the SRIE process.

SHORT CHANNEL EFFECTS

Improved transconductance (g_m) and greatly reduced short channel effects resulted for layer B, as summarised in table 1. Reducing the depth of the channel caused g_m to increase from 420 to 690 mS/mm and a dramatic reduction in the negative threshold voltage shift toward shorter gate length also resulted. The saturated drain current density was improved in layer B by increasing the Si δ-doping intensity from 5×10^{12} cm^{-2} in layer A to 7×10^{12} cm^{-2} in layer B. Excellent uniformity is observed for all the dc parameters, in particular a standard deviation (1σ) in threshold voltage as low as 10 mV is obtained indicating the high degree of uniformity and hence yield offered by the SRIE process. The measured standard deviation in threshold voltage is sensitive to both the gate length and gate channel spacing. We suspect that variations in the surface state charge density in the recess become more important as the physical dimensions of the HEMT are reduced and conclude that a trade off between performance and uniformity has to be made when optimising the pHEMT structure.

Layer	A		B	
Channel Depth (Å)	315		215	
L_g (nm)	165	295	200	330
I_{dss} (mA)	450 (13)	388 (9)	571 (17)	543 (23)
g_m (mS/mm)	387 (13)	419 (8)	686 (38)	686 (8)
V_t (V)	-1.46 (0.065)	-0.98 (0.01)	-0.86 (0.062)	-0.81 (0.037)

Table 1. Summary dc performance, the standard deviation is shown in brackets.

mm-WAVE RESULTS

pHEMTs were characterised using Cascade on wafer probes and Anritsu-Wiltron 360B network analyser from 0-60 GHz and Hewlett-Packard 8510 network analyser from 75 to 110 GHz. The current gain cut off frequency (f_T) derived from the 0-60 GHz measurements is shown in table 2. An f_T of 127 GHz was

Layer	A			B	
Channel Depth (Å)	315			215	
L_g (nm)	120	200	320	200	330
f_T (GHz)	120	99	76	127	89

Table 2. Summary f_T results.

observed for 0.2 μm pHEMTs fabricated on layer B. 0.1 μm pHEMTs are therefore expected to have an f_T of around 150 GHz. f_T and f_{max} were measured for a number of 0.2 μm pHEMTs fabricated on layer B and the results are shown in figures 3 and 4. The best device had an f_T of 127 GHz and f_{max} of 162 GHz, while the mean and 1σ values obtained were 121.1 and 4.6 GHz for f_T and 157.4 GHz and 2.9 GHz for f_{max}, showing a high degree of uniformity and hence RF yield. To qualify the pHEMT for use at w-band, s-parameters were measured from 75 to 110 GHz. Good agreement with a standard HEMT equivalent circuit model fitted to 0-60 GHz data was obtained when the f_T was above the frequency range of the measurement, as shown in figure 5. Note that no fitting has been done to the w-band s-parameters and that no allowance has been made for any difference in calibration between the two sets of measurements. The quality of the agreement is encouraging for the design of MMICs at w-band using pHEMT models obtained at lower frequencies.

CONCLUSIONS

A pHEMT with high performance and high yield has been developed for use at w-band. f_T of up to 127 GHz, f_{max} of up to 162 GHz and g_m of 690 mS/mm were obtained from a 0.2 μm device with excellent uniformity. The use of nano-fabrication techniques, in particular selective reactive ion etching of the gate recess is the key to the high performance and uniformity of our pHEMT technology. Measurements at w-band suggest that MMICs can be designed using pHEMT models obtained at lower frequencies.

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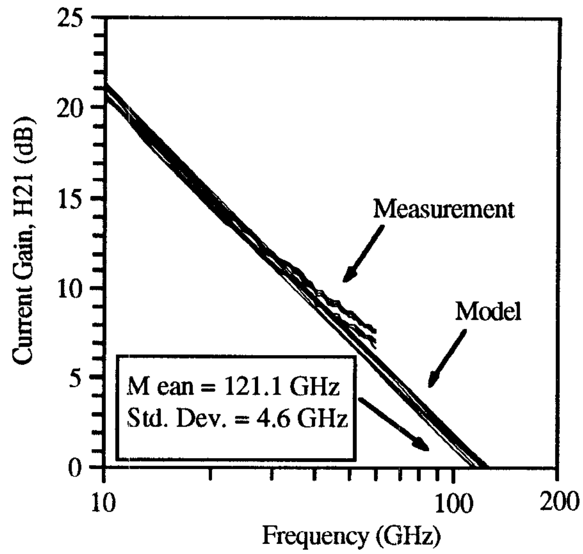

Fig. 3 f_T uniformity of 0.2 μm pHEMTs.

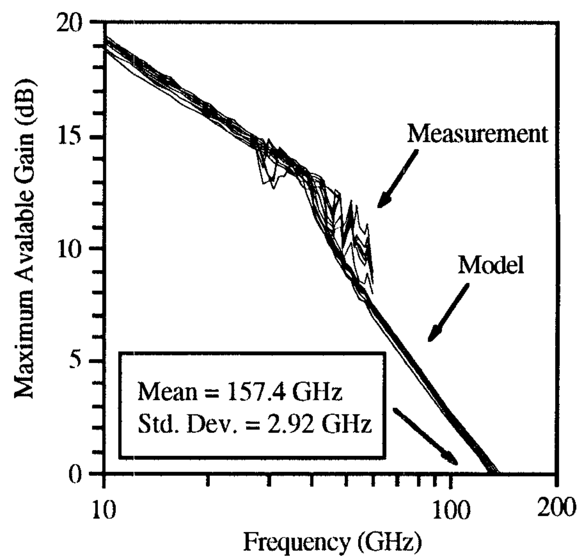

Fig. 4 f_{max} uniformity of 0.2 μm pHEMTs.

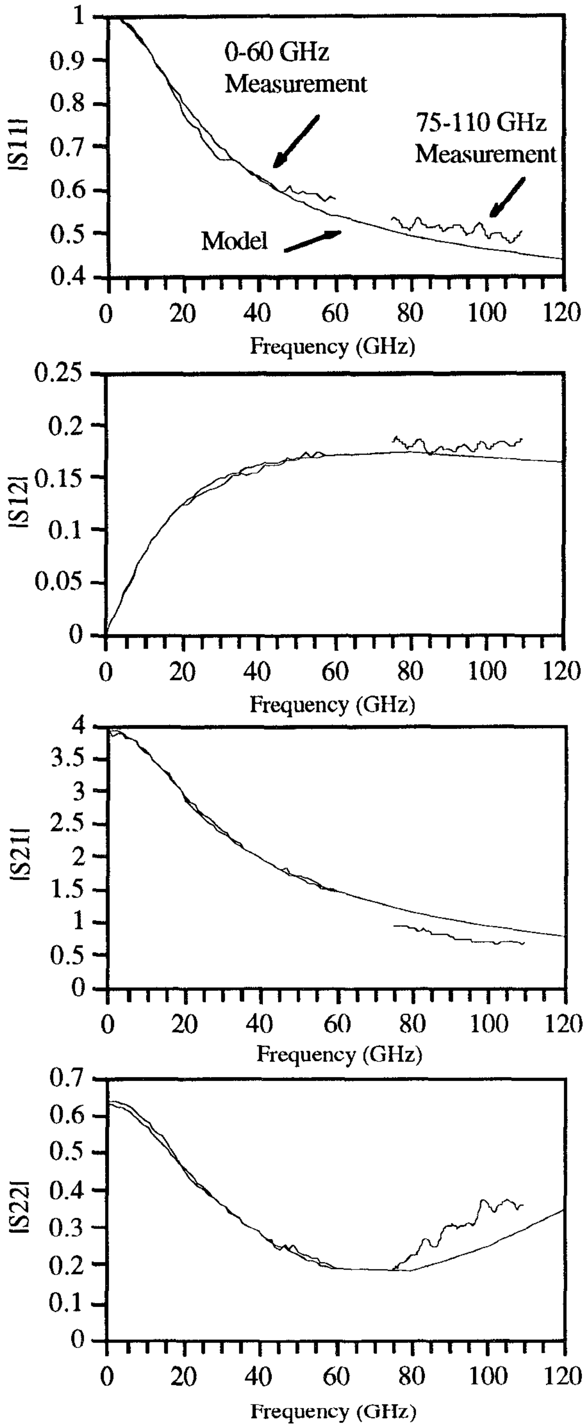

Fig. 5 W-band s-parameter magnitude of a 0.12 μm pHEMT with f_T of 120 GHz

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