InGaAs-InAlAs Heterojunction Technologies for mm and Sub-mm-wave applications: towards quantum limited noise performance.

M. Missous
School of Electrical and Electronic Engineering
The University of Manchester
OUTLINE

• Introduction

• InGaAs-InAlAs pHEMTs

• InGaAs-InAlAs pHEMT limitations

• Possible solutions for lowering noise

• Conclusions
There is great interest in the frequency range between 100GHz and 1THz fuelled mainly by high resolution imaging for many applications.

Sub-millimeter-wave frequencies (> 300 GHz) are now beginning to be addressed by fast transistors based on pHEMT and HBTs.

An all electronic, compact sub-millimeter-wave MMIC technology is key for the realisation of cost effective electronic Terahertz (eTHz) systems.
As low noise devices, the so-called “InP based pHEMT” are particularly attractive. However at sub-100 nm gate length, there are still a number of materials and device topology issues that need addressing.

Short channel effects and parasitics (extrinsics) are the dominant challenges to solve.

For optimising low temperature performance, new epitaxial structures may be required...
Noise limits - 0.1 µm gate length MMIC

Measured MMIC noise temperature vs theoretical quantum limit (Lg=100nm) at Tphys~15-20K. Red line is quantum limit.

(Reference T Gaier et al “AMPLIFIER TECHNOLOGY FOR ASTROPHYSICS”)
Noise limits, recent progress..

Measured noise temperature vs theoretical quantum limit ($L_g=100\text{nm}$) at $T_{\text{phys}}\sim 15-20\text{K}$ and recent (2008) reported 35nm gate data.
Key figures of merit for pHEMT

The cut-off frequency, \( f_T \), of a HEMT is set by the transit time required for an electron to cross the channel.

\[
 f_T = \frac{v_{sat}}{2\pi L_g} = \frac{g_m}{2\pi (C_{gs} + C_{gd})} 
\]

where \( v_{sat} \) is the electron saturation velocity.

The maximum frequency of oscillation, \( f_{max} \), is defined as the frequency at which the unitary power gain, \( U \), is 0\(dB\) and is expressed as:

\[
 f_{max} = \frac{f_T}{2\sqrt{\left(\frac{R_g}{R_s + R_i}\right) / \left(\frac{R_{ds}}{R_g C_{gd}} + 2 f_T R_g C_{gd}\right)}}
\]
\[ f_T = \frac{\langle v_s \rangle}{2\pi L_g} \] ..........................(1)

\[ NF \propto \frac{1}{f_T} \]

\( f_T \) scales with gate length BUT slower than suggested by (1).
Predicted \( f_T \) from (1) is \(~900\text{GHz}\) for In\(_{.7}\)Ga\(_{.3}\)As channel and \(~25\text{nm}\).
State of the art is 610 GHz at 15nm ( but \( F_{\text{max}} \) only 305 GHz.) Jeong et al, 2007
State of the art in $f_{\text{max}}$ is 1.2 THz at 35 nm (but $f_{T}$ only 480 GHz.)
In$_x$Ga$_{(1-x)}$As-In$_y$Al$_{(1-y)}$As pHEMT Epitaxial layer structures.

**Device Overview**

- **Lateral scaling (Lg and d$_{sd}$)**
  - → high field effects
- **Horizontal scaling**
  - **Breakdown issues**
  - **Leakage issues**
  - **Aspect ratio (Lg/d) > 3**
  - **Difficult to obtain a high ft and fmax simultaneously**
    - High ft requires low d$_{sd}$ which results in short channel effects
      - (drain induced barrier lowering, high output conductance)
    - There is also an increase in the gate-drain capacitance C$_{gd}$ and this reduces fmax of the device.
Device Equivalent circuit Model

\[ NF_{\text{min}} = 1 + K_F \omega (C_{gs} + C_{gd}) \sqrt{\frac{R_s + R_g}{G_m}} \]

\[ F_{\text{min}} (dB) = 10 \log \left( 1 + k' (f / f_T) \sqrt{g_m (R_g + R_s)} \right) \]
In$_x$Ga$_{(1-x)}$As-In$_y$Al$_{(1-y)}$As pHEMT Epitaxial layer structures.

Flexibility in band gap engineering: 0.36eV $\rightarrow$ 2 eV
Interlude: Some SKADS InGaAs-InAlAs pHEMT developments: Leakage currents issues.

Large band gap $\text{In}_y\text{Al}_{(1-y)}\text{As}$ tensile stained supply layer ($y=0.5 \rightarrow 0.25$) $d=15\ \text{nm}$

On-state leakage current at $V_{DS}=1\text{V}$ (solid line) and $V_{DS}=1.5\text{V}$ (dashed line) for a variety of $\text{In}_y\text{Al}_{(1-y)}\text{As}$ supply layer materials. For $y=0.25$, the leakage is reduced by over $10\times$. 
What about low temperature performances?

- For most applications, pHEMT are optimised for room temperature (~300K) performance.
  - Optimise mobility and electron carrier densities

- Low temperature optimisations not necessarily the same.
Mobility, carrier conc. and conductivity as function of spacer thickness (A)

Conductivity maximum at lower separation (high electron scattering) but at RT phonon scattering is dominant mechanism.
At 77K, Conductivity maximum at higher separation (low electron scattering).
At low temperatures phonon scattering lower.
Device implication → issue with aspect ratio? Maybe not at Lg=100nm
Can still engineer increase of conductivity down to 4K.
Mobility and sheet carrier concentration as function of temperature for InGaAs-InAlAs materials\(^*\).
Note conductivity saturation at \(~ 30K\).
..and observed Noise Figure as a function of operating temperature.

@ 12GHz data, single transistor, 0.5µm gate length
4F1 Noise Temperature Susceptibility Test  22 Apr 2006
+ 60K mean point from TV tests + RT LNA points for 4F1A1 and 4F1A2

Data courtesy University of Manchester Plank team.
4F1 Noise Temperature Susceptibility Test 22 Apr 2006
+ 60 K mean TV point, unsuppressed zero

Data courtesy University of Manchester Plank team.
CONCLUSIONS

- State of the at InGaAs-InAlAs pHEMT with $f_T$ and $f_{\text{max}}$ of 500 GHz and $\sim 1$THz are beginning to emerge at gate length of $\sim 30$nm.

- We are still a fair way from can be achieved by at least a factor of 2 in $f_T$.

- Reaching the quantum limit may be achieved with this material system by proper manipulation of scaling and band gap engineering of the $\text{In}_x \text{Ga}_{(1-x)} \text{As-In}_y \text{Al}_{(1-y)} \text{As}$ system.

- $\text{In}_x \text{Ga}_{(1-x)} \text{As-In}_y \text{Al}_{(1-y)} \text{As}$ is moving away from being a specialised niche technology and is road mapped for high volume, post-CMOS electronics at the 22nm node.
InGaAs-InAlAs pHEMTs are on the Road Map..