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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

The University of Manchester

Microelectronics and Nanostructures group

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.

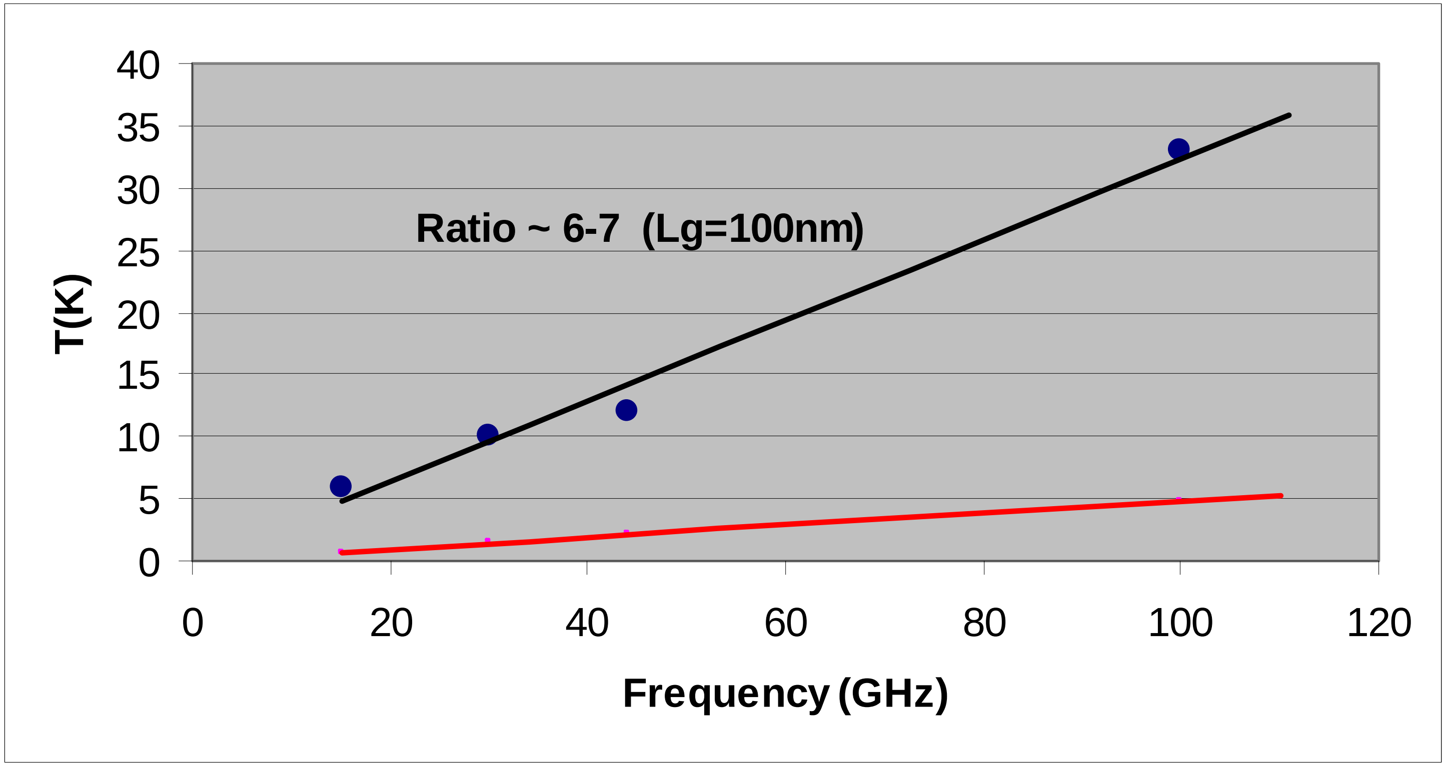
An all electronic, compact sub-millimeter-wave MMIC technology is key for the realisation of cost effective electronic Terahertz (eTHz) systems.

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...

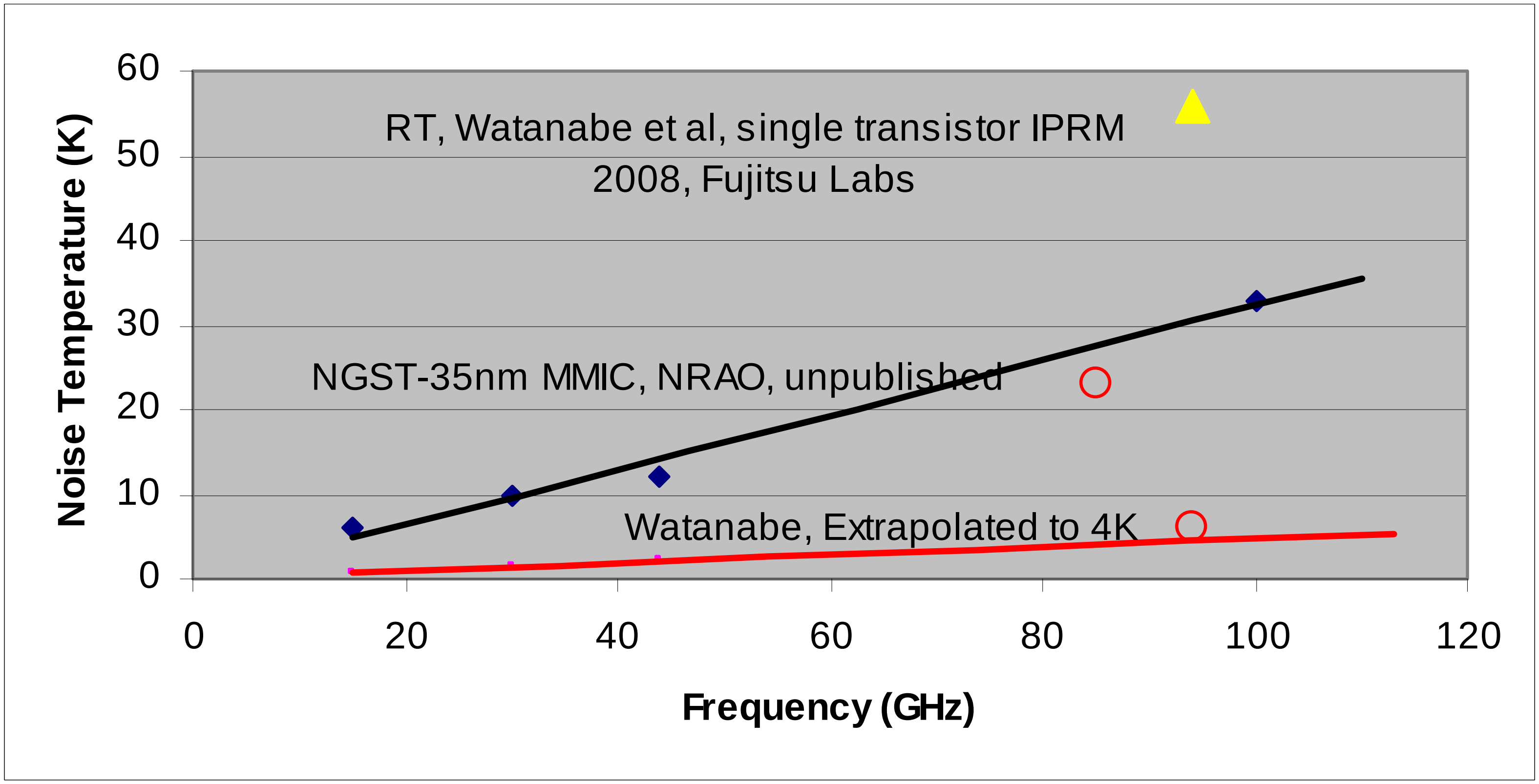
Noise limits-0.1 µm gate length MMIC



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 (Lg=100nm) at Tphys~15-20K and recent (2008) reported 35nm gate data.

Key figures of merit for pHEMT

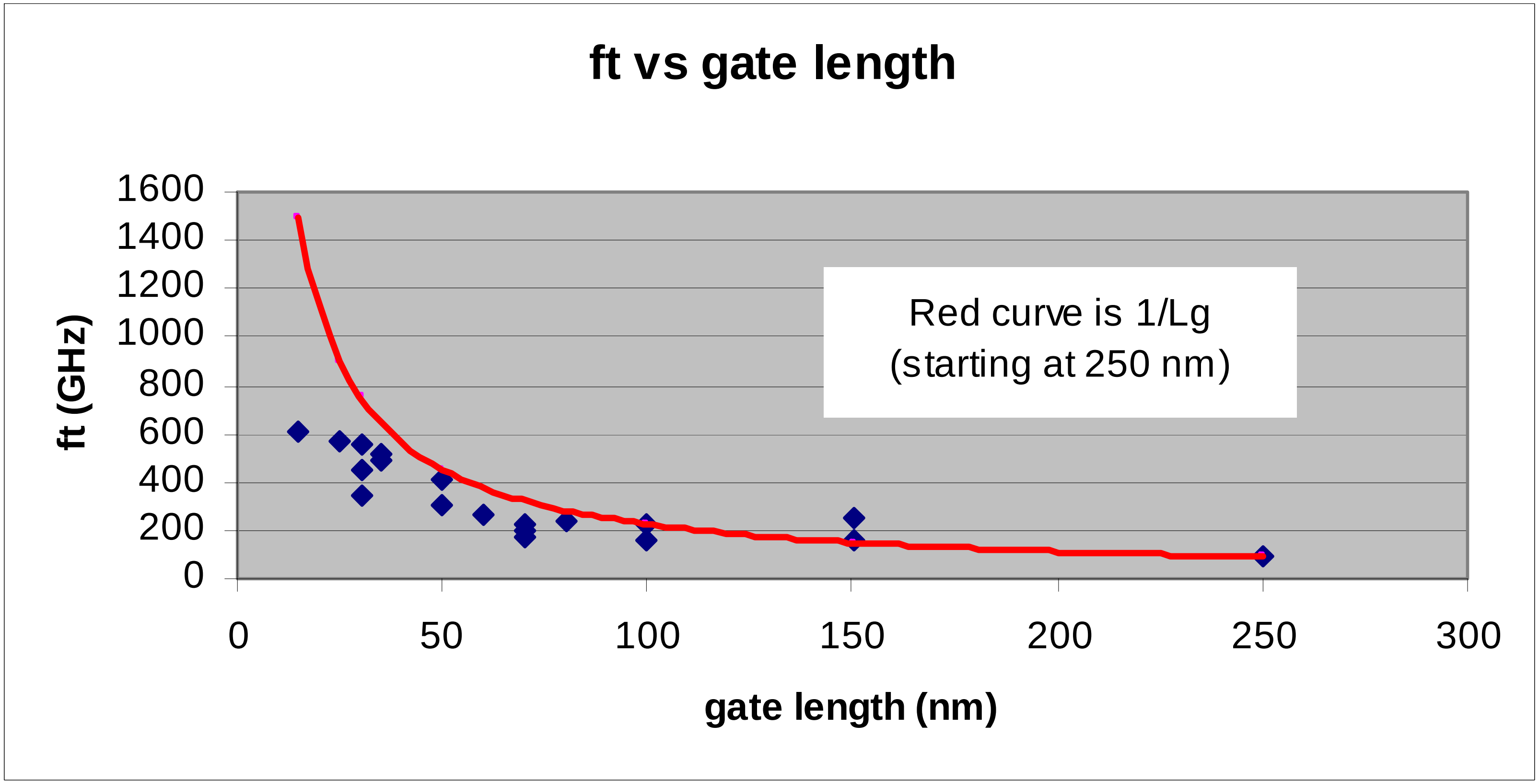
The cut-off frequency, f_T, of a HEMT is set by the transit time required for an electron to cross the channel.

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

where v_{sat} is the electron saturation velocity.

The maximum frequency of oscillation, *fmax*, is defined as the frequency at which the unitary power gain, *U*, is 0*dB* and is expressed as:

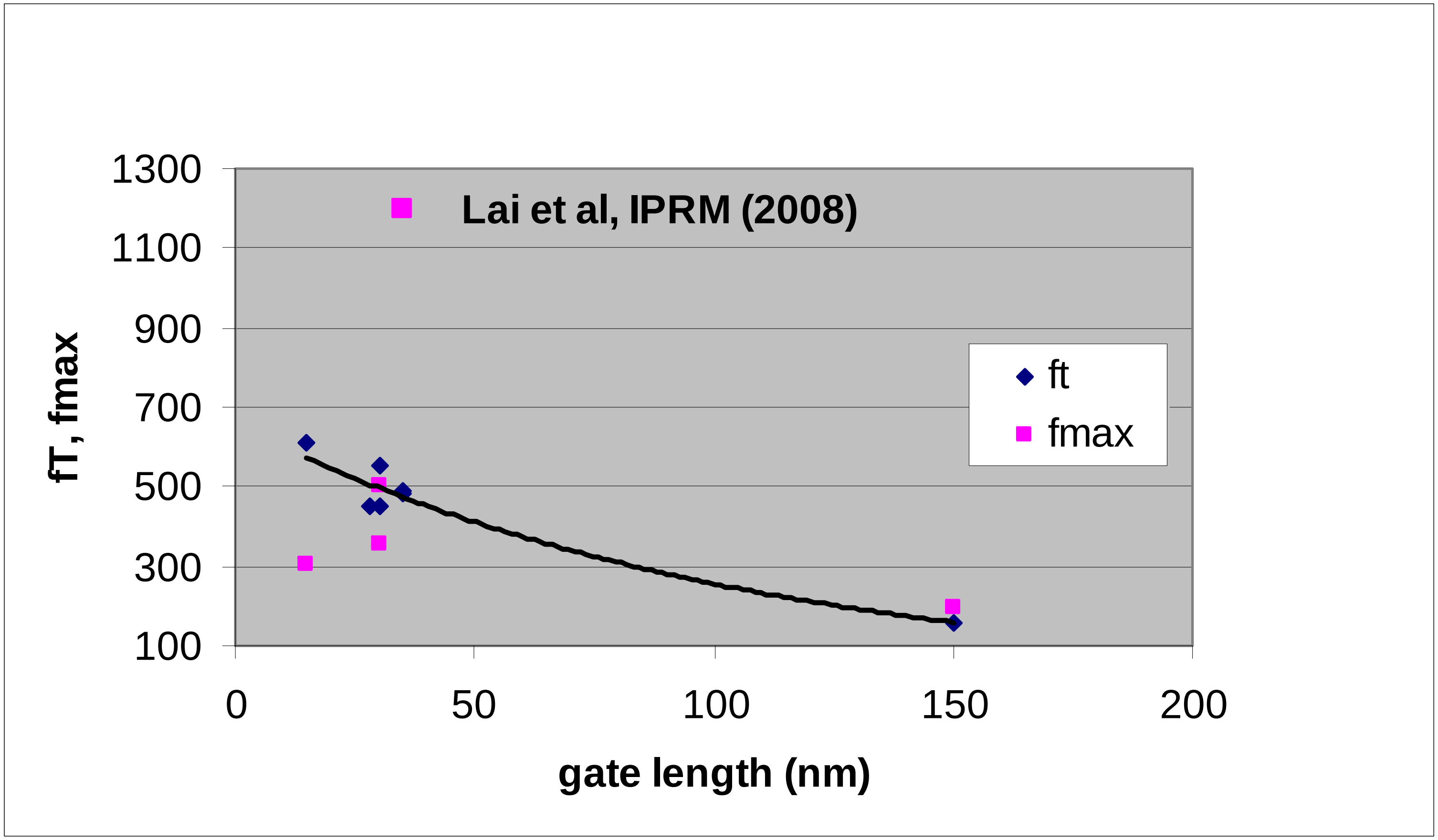
$$f_{\max} = \frac{f_T}{2\sqrt{(R_g + R_s + R_i)/R_{ds} + 2 f_T R_g C_{gd}}}$$



$$f_T = \frac{< v_s >}{2\pi L_g} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$NF \propto 1/ f_T$$

f_T scales with gate length BUT slower than suggested by (1).
Predicted f_T from (1) is ~900GHz for $In_{.7}Ga_{.3}As$ channel and ~25nm.
State of the art is 610 GHz at 15nm (but F_{max} only 305 GHz.) Jeong et al, 2007



f_T and f_{max} vs Lg

State of the art in f_{max} is 1.2 THz at 35 nm (but f_T only 480 GHz.)
Lai et al, IPRM (2008)

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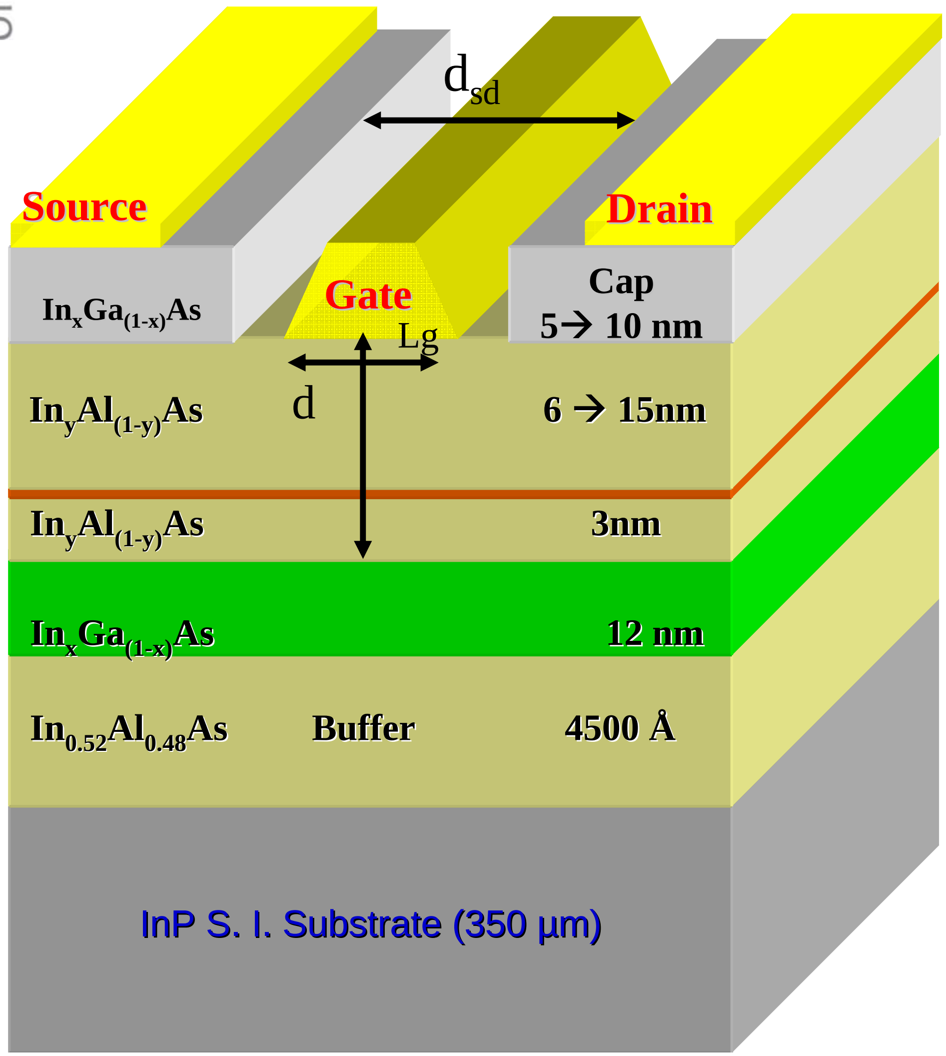
$In_xGa_{(1-x)}As$-$In_yAl_{(1-y)}As$ pHEMT Epitaxial layer structures.

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 Cgd and this reduces fmax of the device.***

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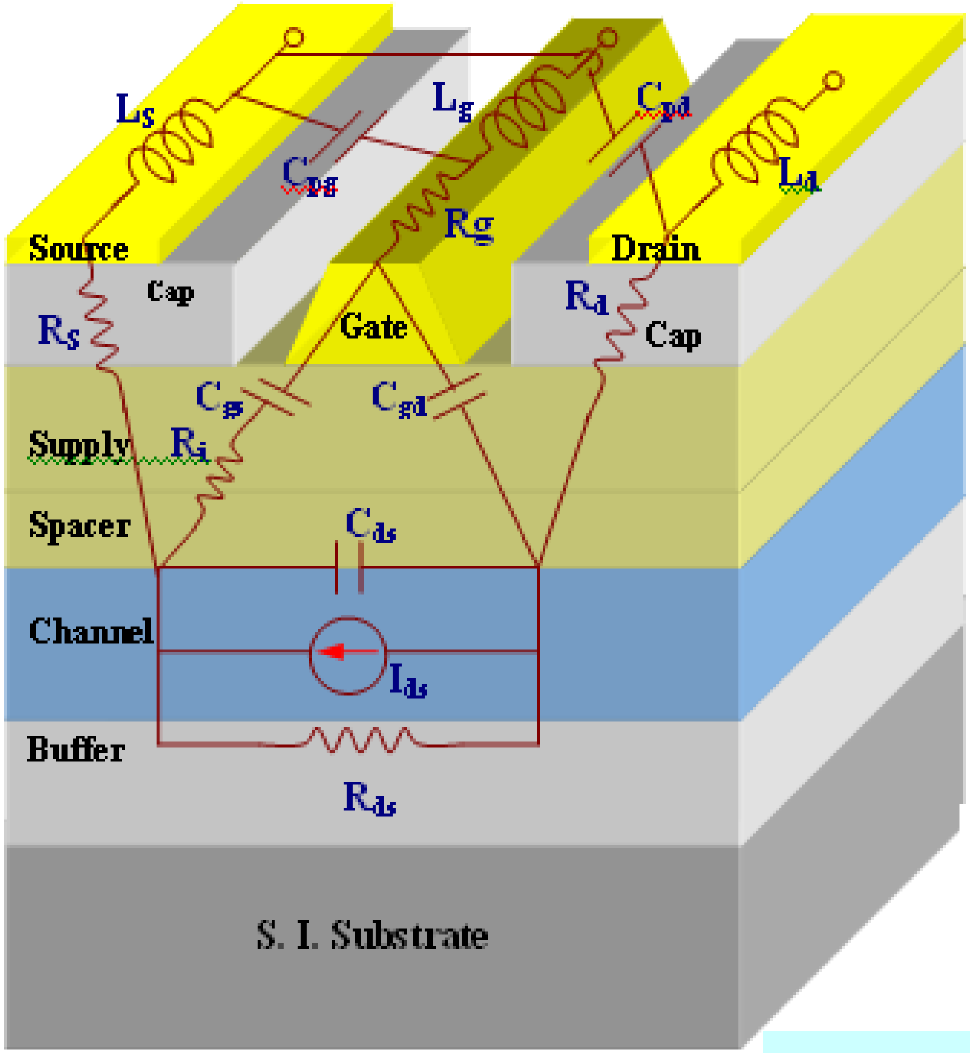
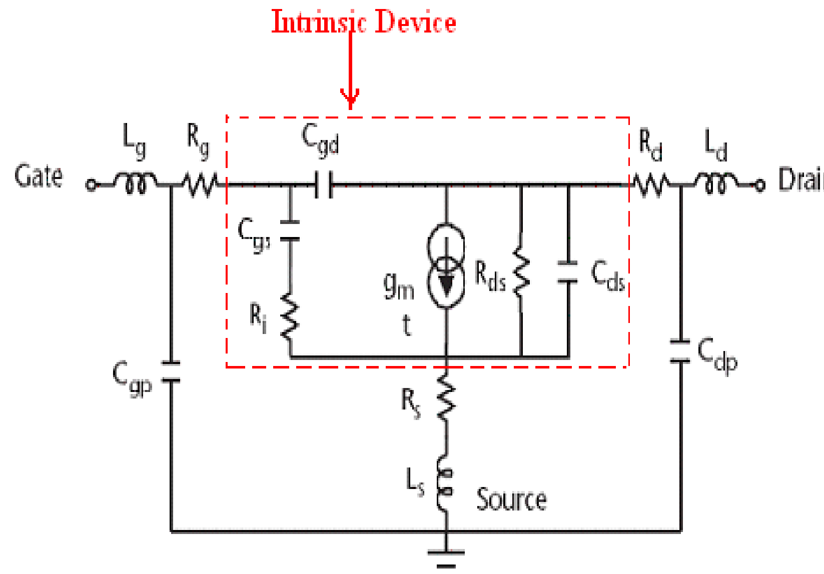
Device Equivalent circuit Model





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

$$F_{min}(dB) = 10\log\left(1+k'(f/f_T)\sqrt{g_m(R_g+R_s)}\right)$$

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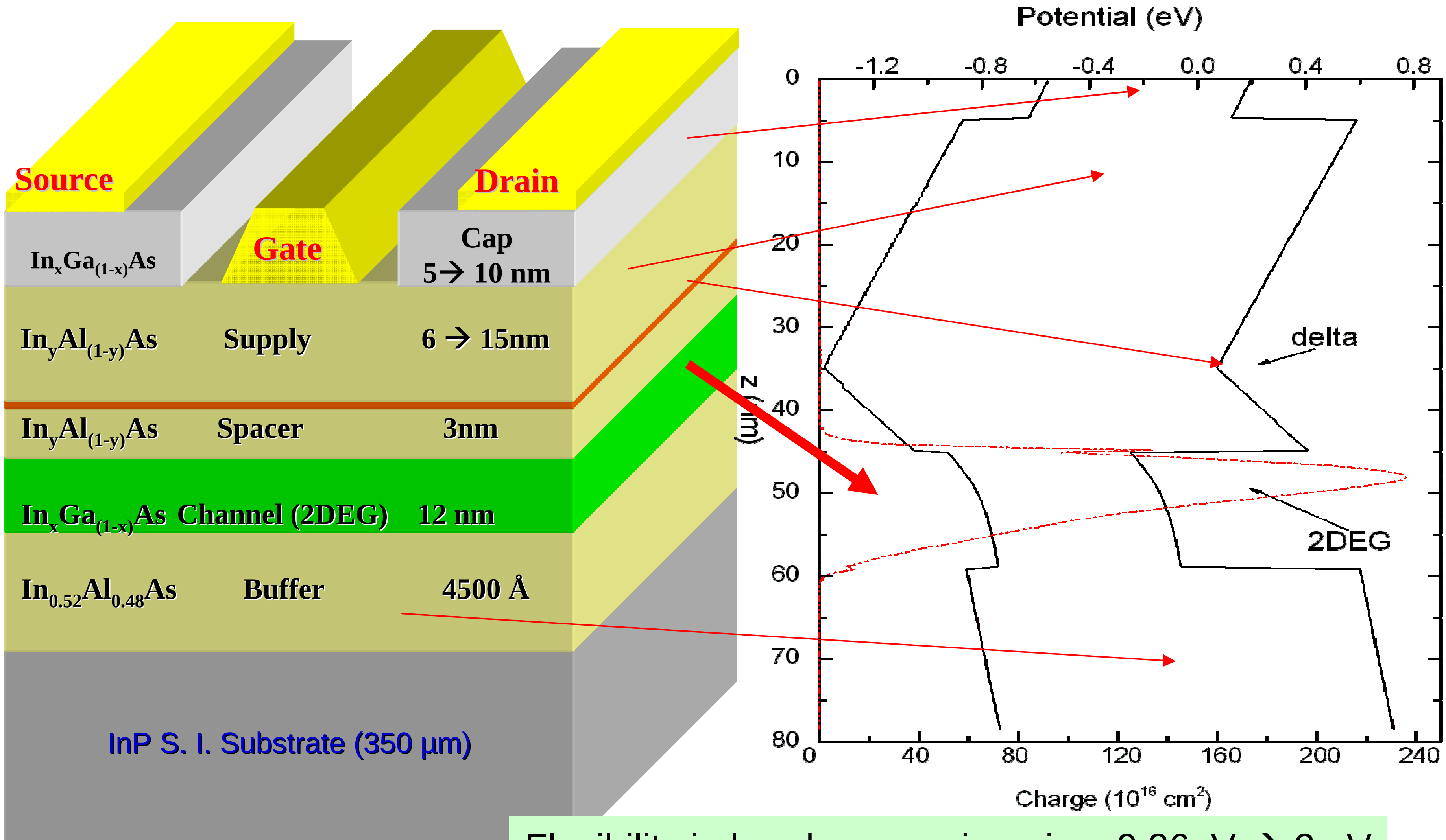

Flexibility in band gap engineering: 0.36eV → 2 eV

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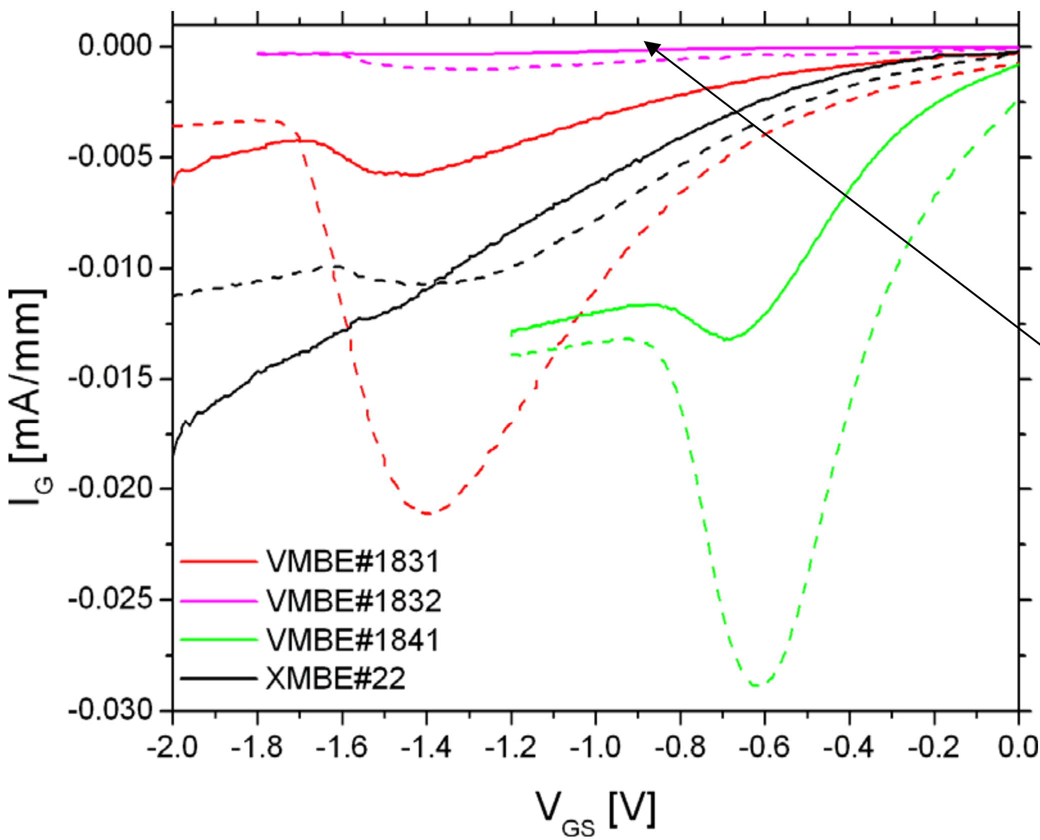
Interlude : Some SKADS InGaAs-InAlAs pHEMT developments: Leakage currents issues.

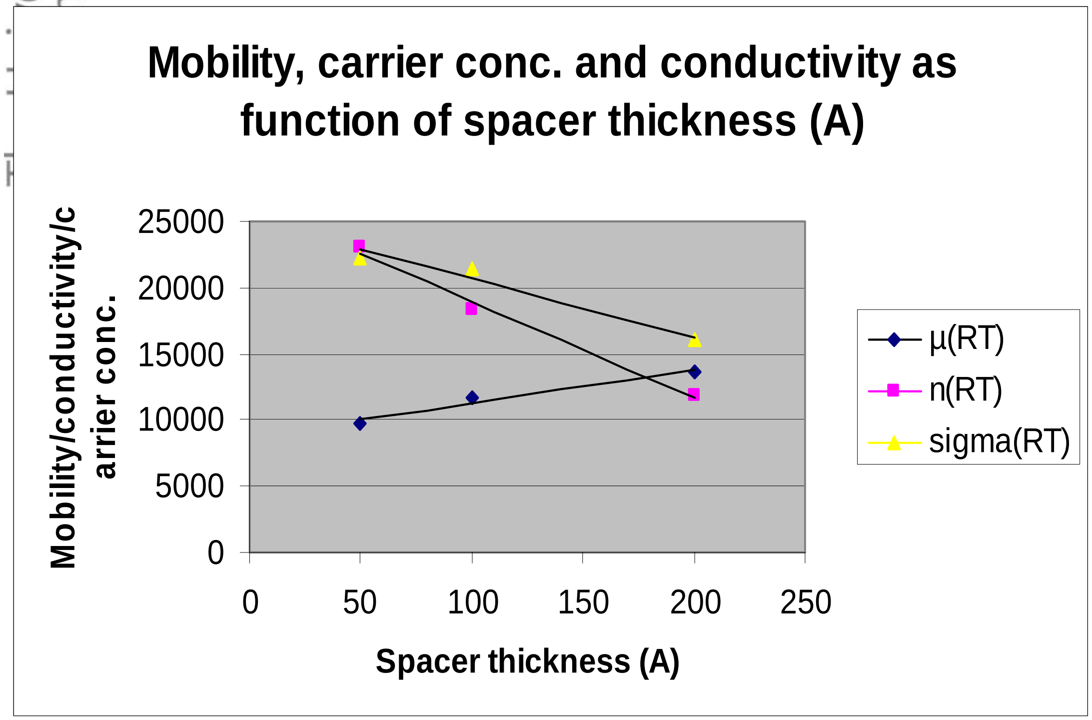


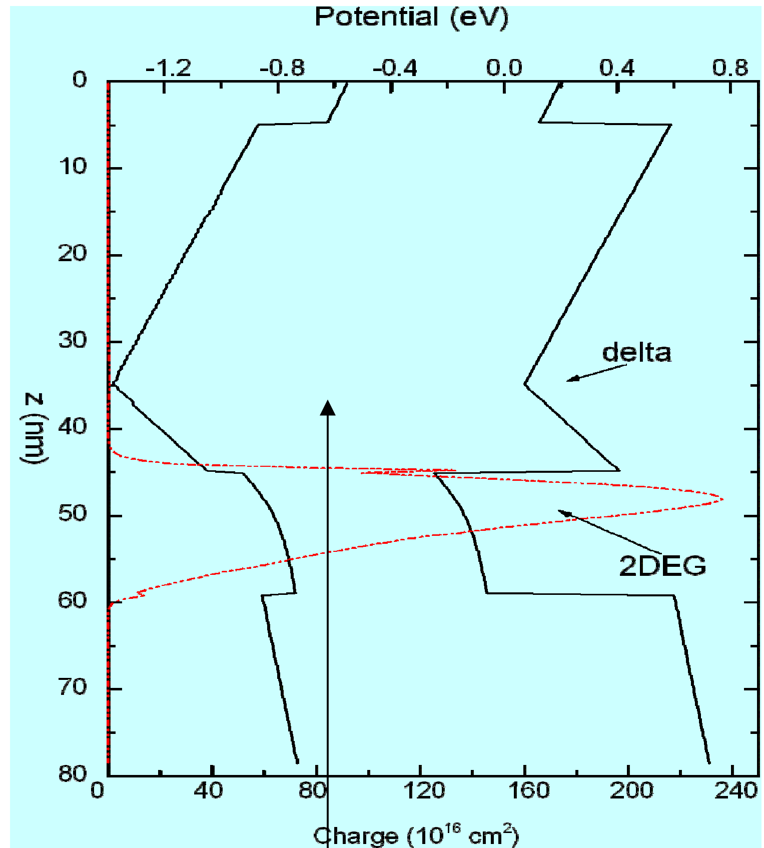
Large band gap $In_yAl_{(1-y)}As$ tensile stained supply layer (y=0.5 → 0.25)
d= 15 nm

On-state leakage current at VDS=1V (solid line) and VDS=1.5V (dashed line) for a variety of $In_yAl_{(1-y)}As$ supply layer materials. For y= 0.25, the leakage is reduced by over 10x.

What about low temperature performances?

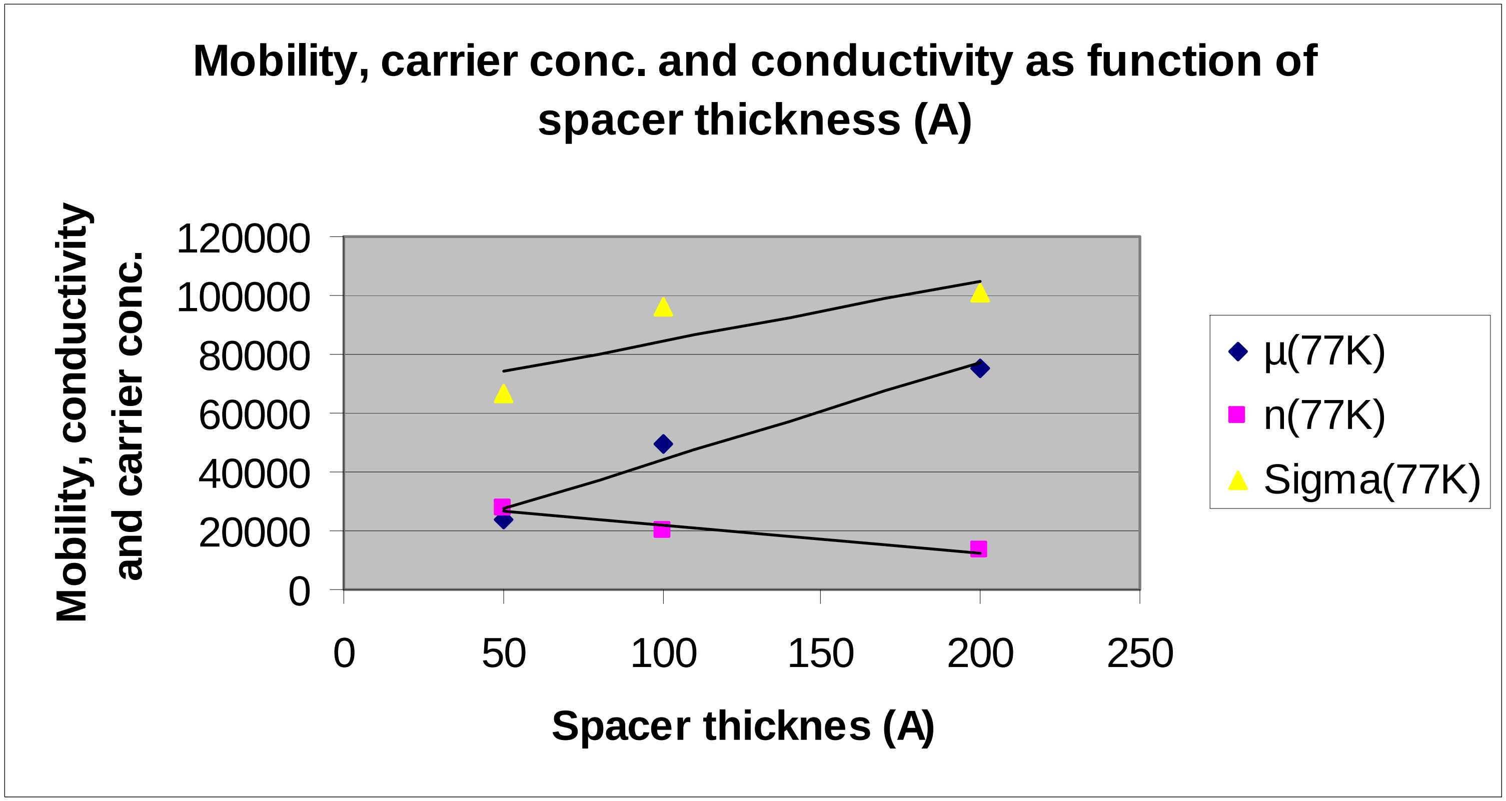
- For most applications, pHEMT are optimised for room temperature (~300K) performance.
  - Optimise mobility and electron carrier densities
- Low temperature optimisations not necessarily the same.



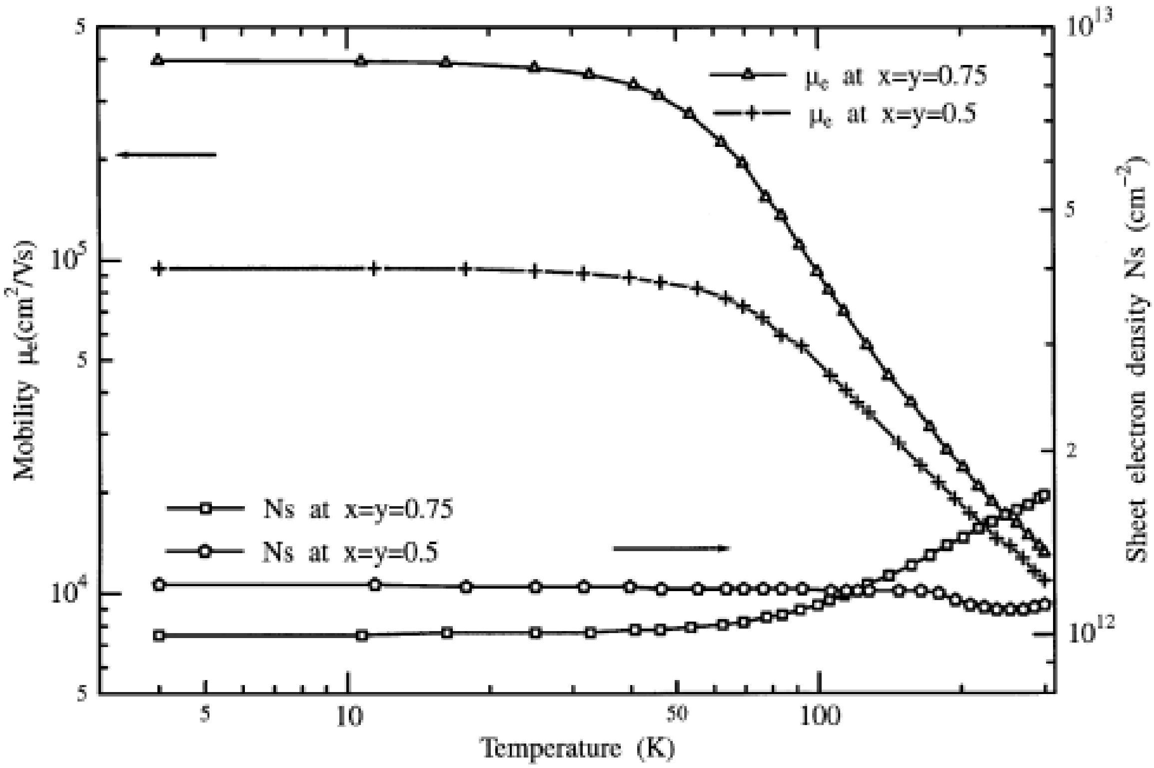


Conductivity maximum at lower separation (high electron scattering) but at RT phonon scattering is dominant mechanism.

Spacer thickness control Ns and scattering (mobility)



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.

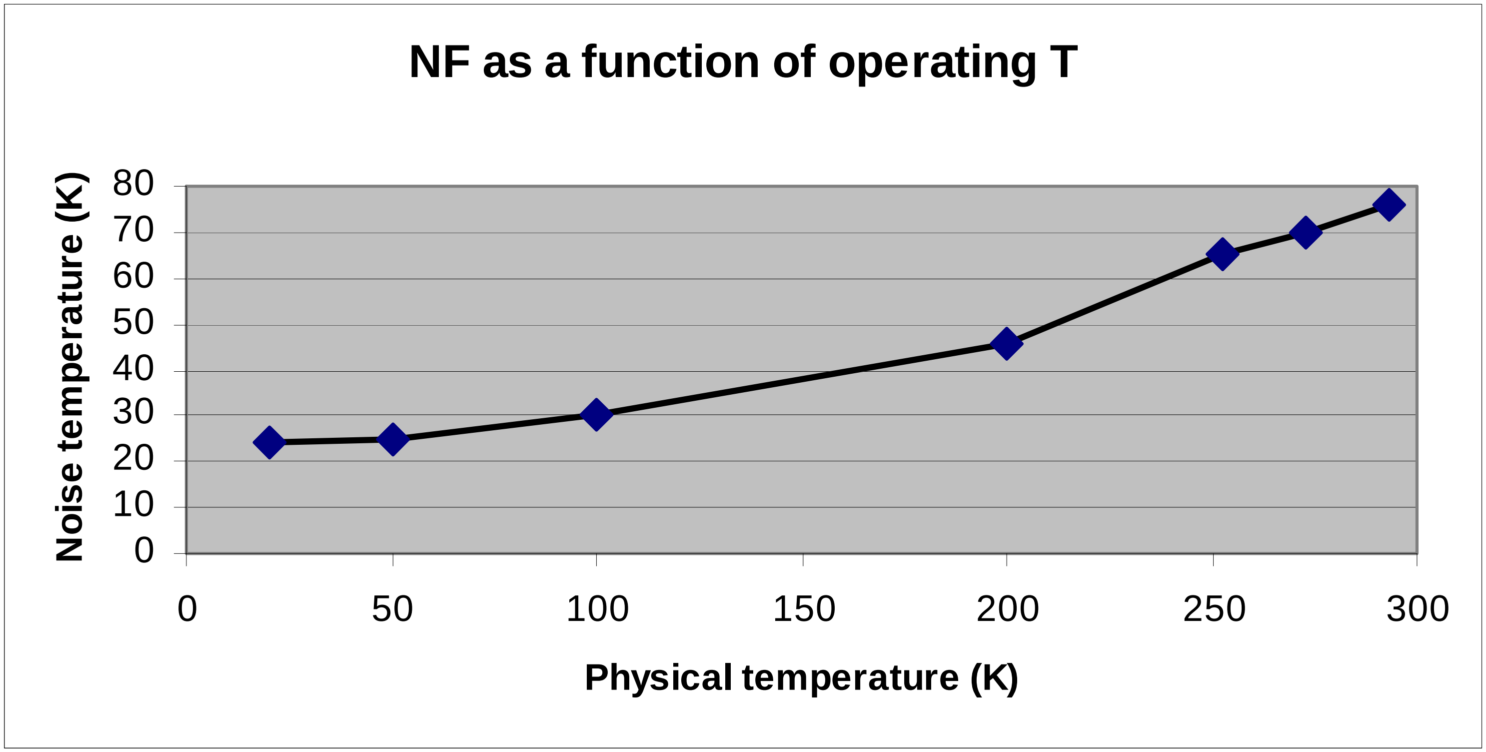


Spacer layer ~ 5nm

Mobility and sheet carrier concentration as function of temperature for InGaAs-InAlAs materials[*].
Note conductivity saturation at ~ 30K.

[*]S Goz et al, JCG,201/202, 749(1999)

..and observed Noise Figure as a function of operating temperature.



@ 12GHz data, single transistor, 0.5µm gate length

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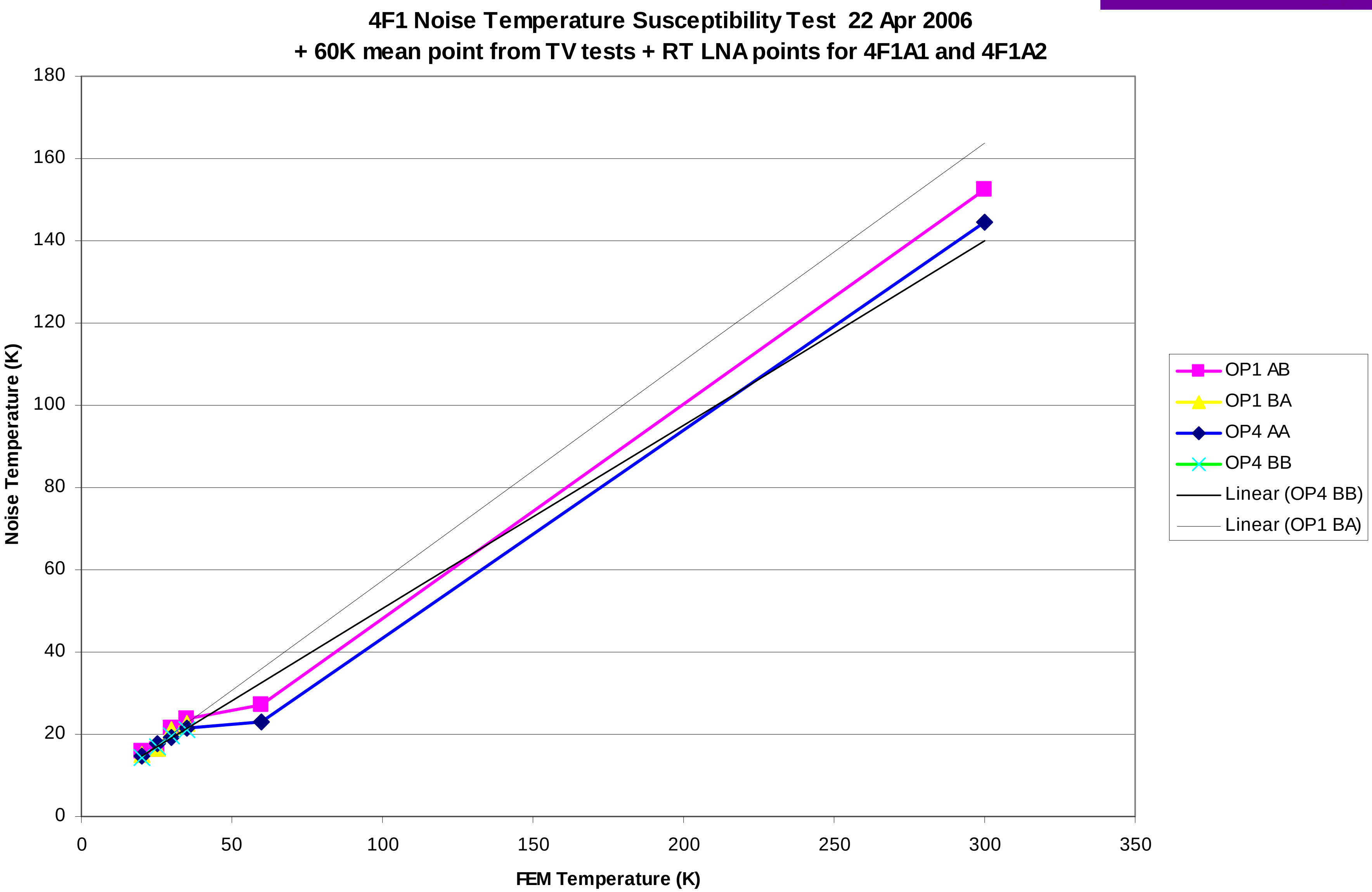

Data courtesy University of Manchester Plank team.

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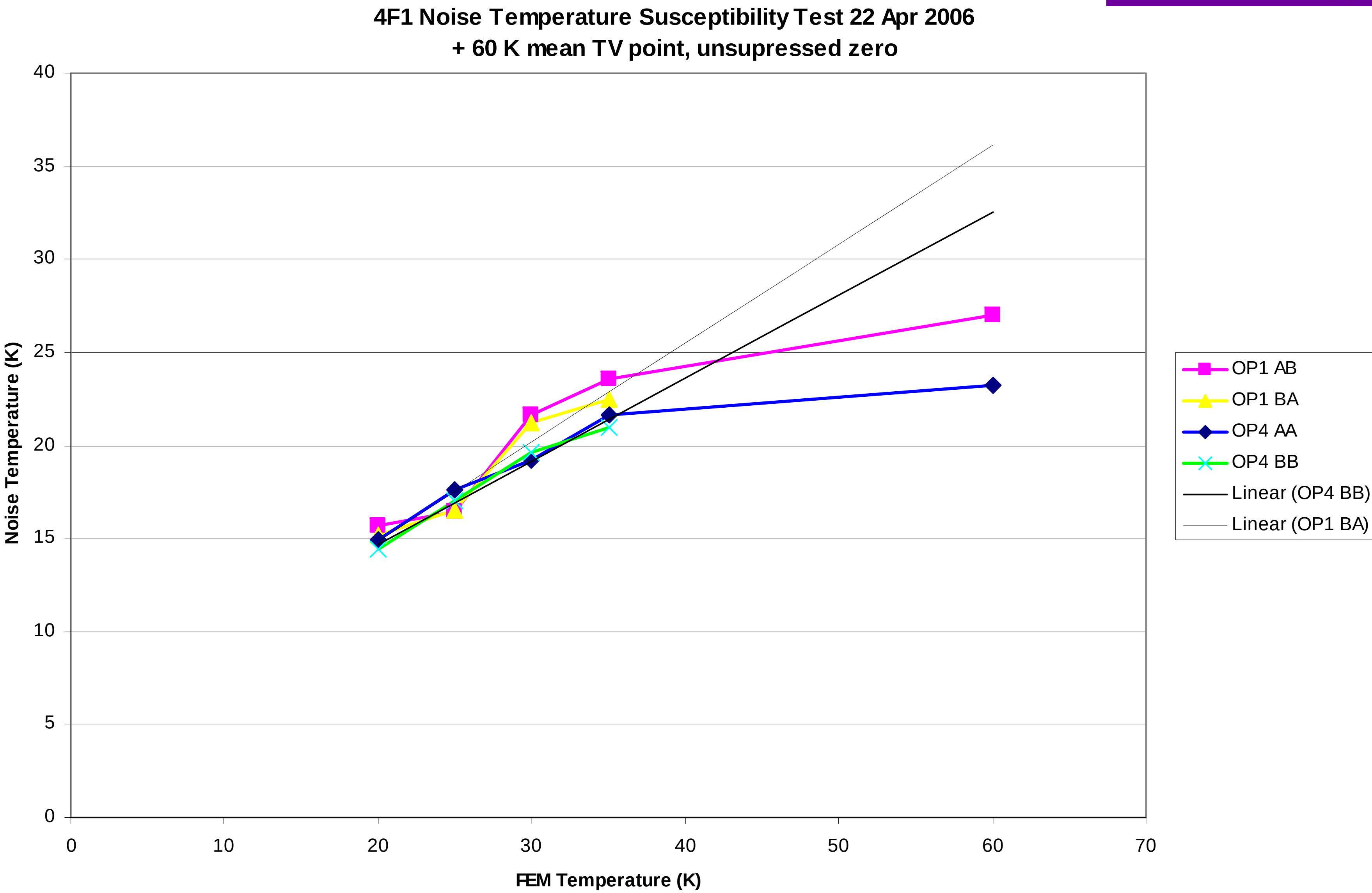

Data courtesy University of Manchester Plank team.

CONCLUSIONS

- State of the at InGaAs-InAlAs pHEMT with f_T and f_{max} of 500 GHz and ~ 1THz are beginning to emerge at gate length of ~ 30nm.
- 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 $In_xGa_{(1-x)}As$-$In_yAl_{(1-y)}As$ system.
- $In_xGa_{(1-x)}As$-$In_yAl_{(1-y)}As$ is moving away from being a specialised niche technology and is road mapped for high volume , post-CMOS electronics at the 22nm node.

INTERNATIONAL TECHNOLOGY ROADMAP FOR SEMICONDUCTORS 2007 EDITION RADIO FREQUENCY AND ANALOG/MIXED-SIGNAL TECHNOLOGIES FOR WIRELESS COMMUNICATIONS

Year of Production	2007	2008	2009	2010	2011	2012	2013	2014	2015
Gate Length (nm)	100	70		50		35		25	
Ft (GHz)	200	250		350		420		500	
Breakdown (Volts)	4	3		2.5		2		1.5	
Imax(mA/mm)	500	600		550		500		500	
Gm(S/mm)	1.1	1.5		1.8		2		2.2	
Fmin(dB) at 94GHz	1.5	1.3		1.1		1		. 9	
Associated Gain (dB) (94 GHz)	8	9		11		12		14	

Manufacturable solutions exist, and are being optimized
Manufacturable solutions are known
Interim solutions are known
Manufacturable solutions are NOT known

InGaAs-InAlAs pHEMTs are on the Road Map..