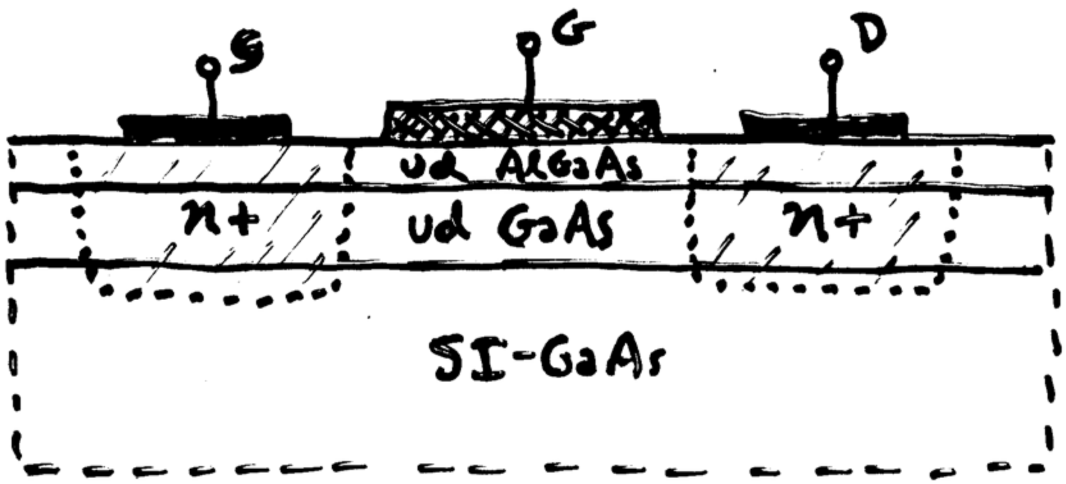
Lecture 12 - Heterojunction FETs - HIGFETs, HEMTs

- **HIGFETs** - undoped channel HJFETs
  - Basic structure
  - Complementary HIGFET logic
- **HMETs**
  - Basic structure
  - GaAs-based devices
  - InP-based devices
- **Current situation**
  - Hot areas today:
    - High temperature FETs: SiC and GaN HFETs
    - Metamorphic InGaAs HEMTs on GaAs
  - The status of integration
    - Digital ICs
    - MMICs

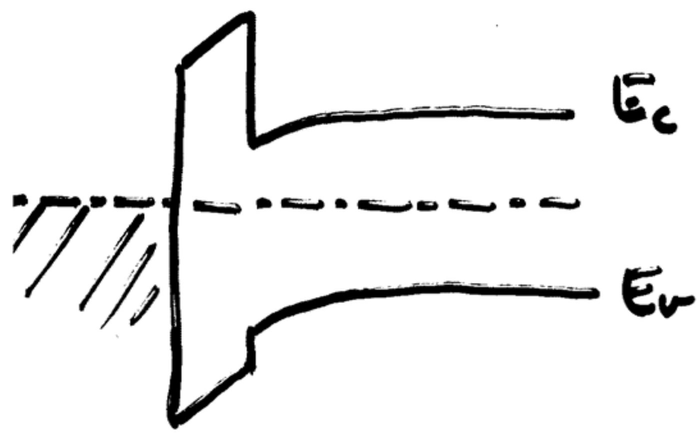
Heterojunction FETs - the undoped HJFET
(the HIGFET - heterojunction insulating gate FET)

Structure:

- undoped hetero-structure
- the HFET analog of the inverted channel MOSFET



Unbiased bands under the gate:

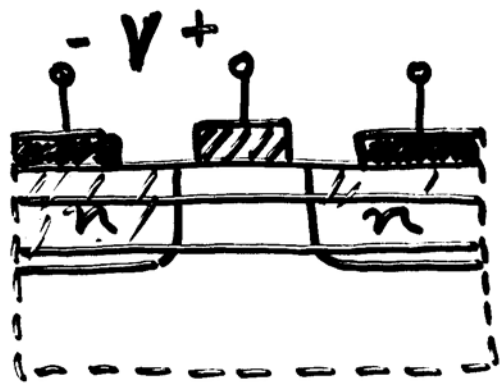


Carriers are drawn into the channel by the gate and from the doped regions. They can be either holes or electrons.

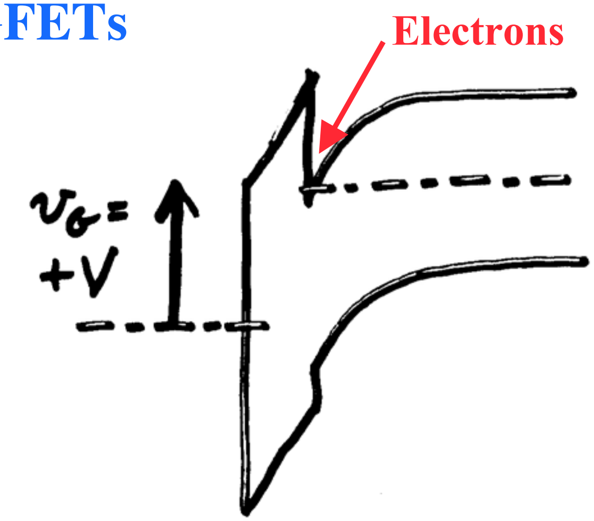
Undoped HJFET - the HIGFET

Complementary devices: the same epi-structure can be used to make n-channel and/or p-channel HIGFETs

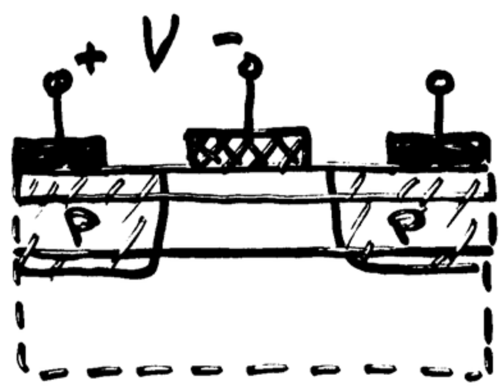
- We can make both n- and p-channel FETs from the same epi-structure.



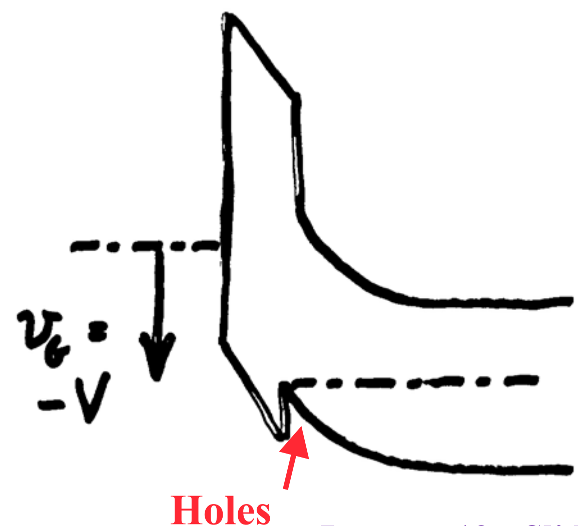
n-channel



- Issues:
  - p-channel device still suffer from low hole mobility
  - sources and drain resistances are a major concern
  - can only be enhancement mode



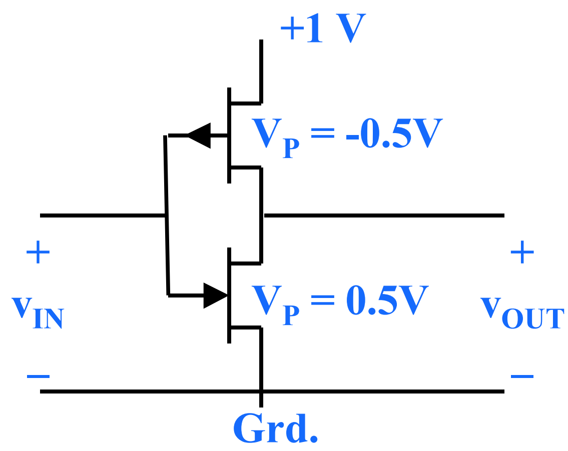
p-channel



Developed at Honeywell

Complementary HIGFET Logic - HFET CMOS

Inverter with n- and p-channel enhancement mode HIGFETs

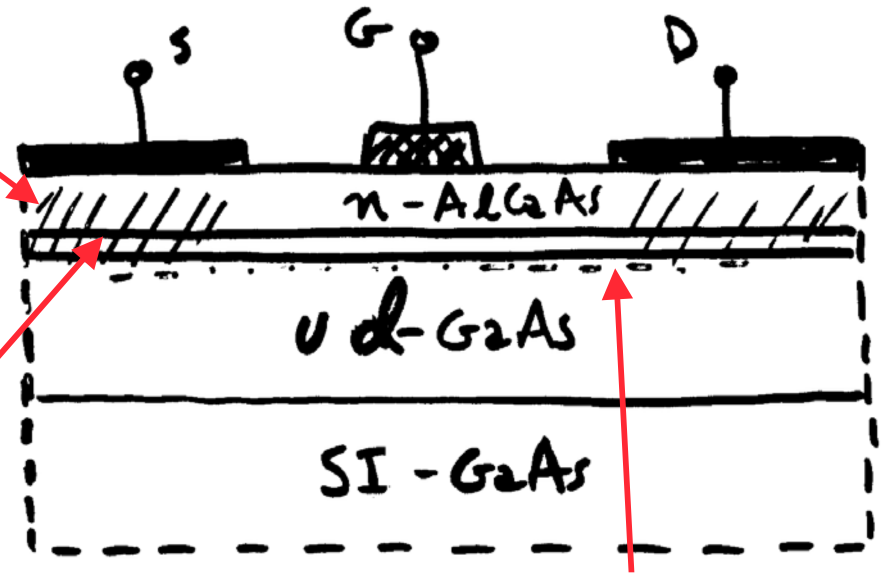


v_{IN}	n-channel	p-channel	v_{OUT}
0 V (lo)	Off	On	1 V (hi)
1 V (hi)	On	Off	0 V (lo)

Just as with CMOS, the attraction is that static power is eliminated because one device is always off in steady-state.

Heterojunction FETs - the HEMT; also called MODFET, TEGFET, and SDFET)

20 to 30 nm of doped AlGaAs

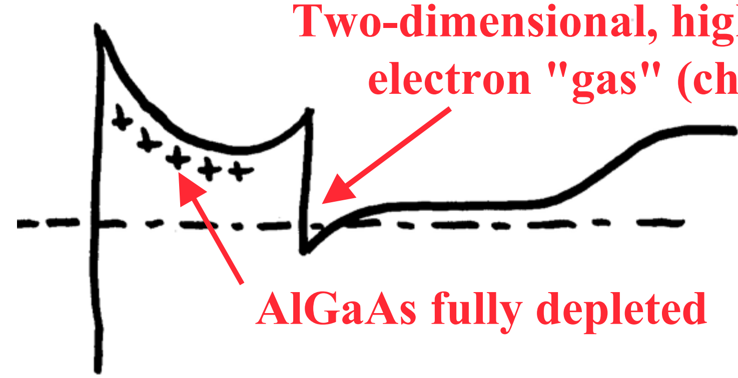


<u>Structure</u>:
- doped WBG layer over an undoped NBG layer

Undoped AlGaAs spacer, ≈ 5 nm

Two-dimensional, high mobility electron "gas" (channel)

Conduction band edge under an unbiased gate:



AlGaAs fully depleted

Typical doping level in AlGaAs: 10^{18} cm^{-3}

Typical sheet carrier density in channel: 10^{12} cm^{-2}

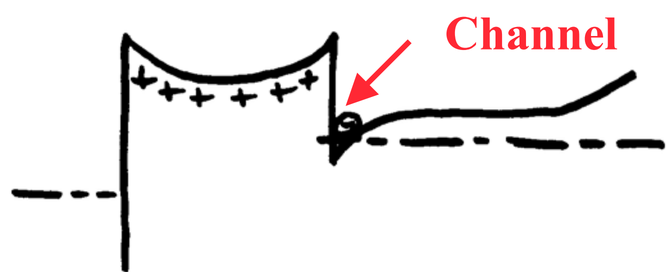
Modulation doped HJFETs - the HEMT

The most important problems associated with the HEMT deal with the n-doped AlGaAs gate

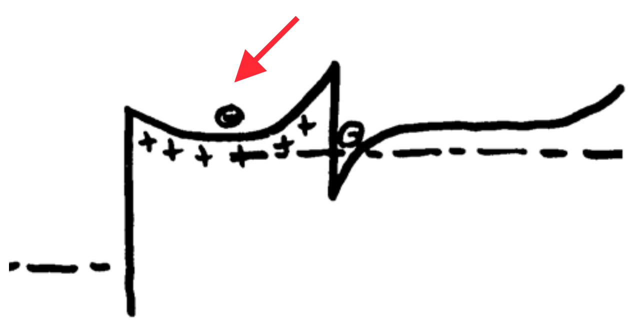
<u>To understand this, consider turning the channel on</u>:

- The maximum forward bias that can be applied to the gate is set by the onset of conduction in the AlGaAs

Moderate forward bias:
n-AlGaAs depleted



Excessive forward bias:
n-AlGaAs populated



HEMTs - the DX Center problem

Solving the problem of AlGaAs turn-on:

- The obvious solution is to increase the Al concentration to increase this layer's bandgap.
- The problem is the appearance of DX centers above ≈ 23% Al.

(Image deleted)

See Pearson and Shah in: Sze, S.M., ed., High Speed Semiconductor Devices New York: Wiley, 1990.

DX Center: A deep level associated with the L-band minimum

HEMTs - the DX Center problem, cont.

Why DX centers are a problem:

They cause problems at low temperatures:

- I-V collapse
- persistent photo-conductivity

I-V collapse:

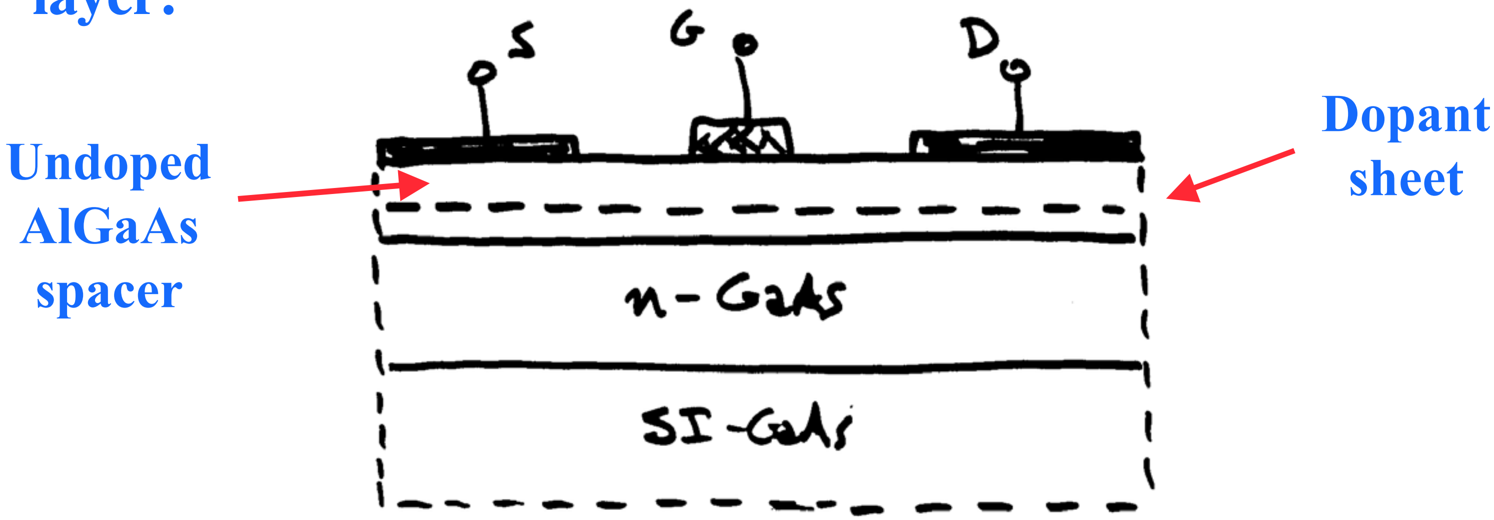
Al fraction must be less than 20% (barrier ≈ 0.16 eV)

The solution: Don't make the barrier higher, make the well deeper by adding indium. This involves strained layers….

Pseudomorphic HEMTs (PHEMTs)

HEMTs - Delta Doping

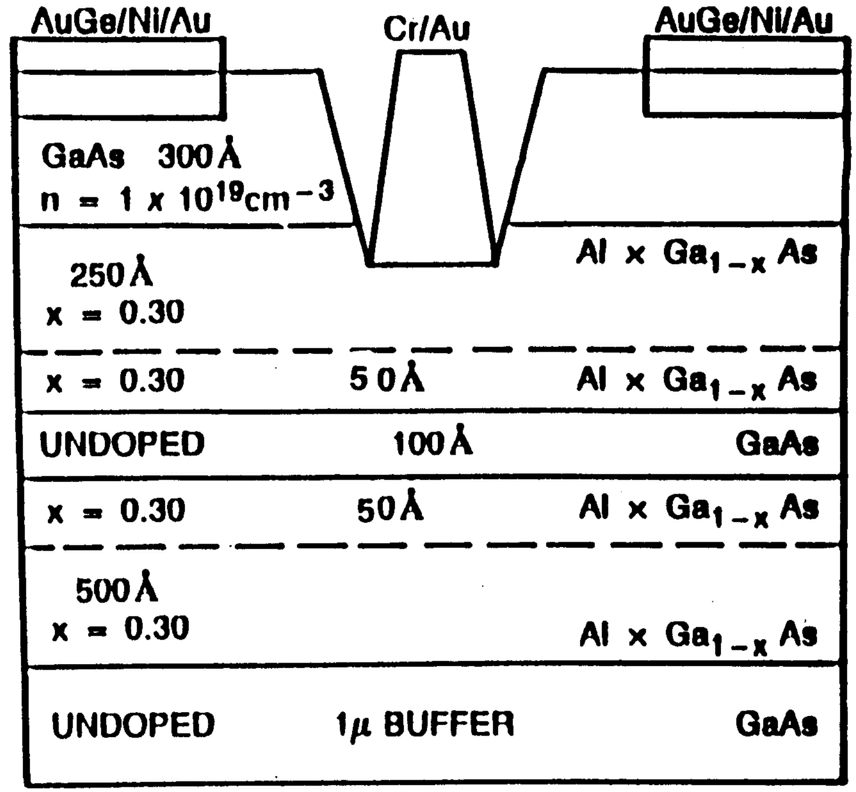
The parallel conduction problem can be reduced by not doping the entire AlGaAs, but instead to put the dopants in a single layer:



- Delta doping yields higher channel concentrations

HEMTs - Delta Doping, cont.

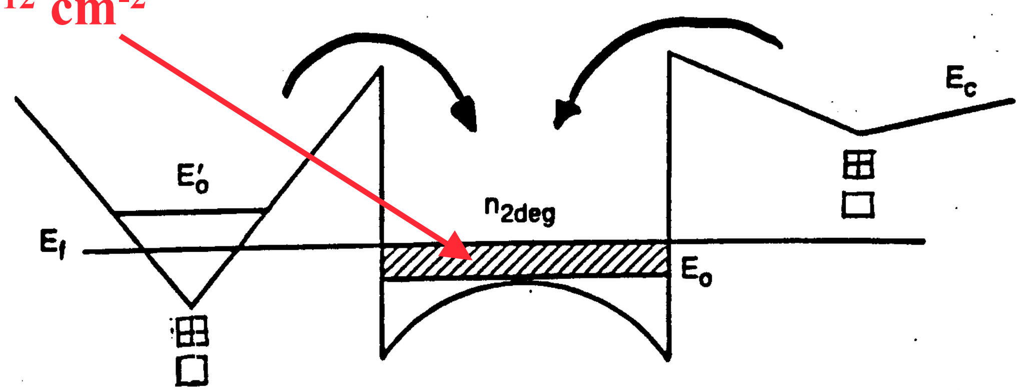
An example of a device with a delta-doped AlGaAs barrier above, as well below, the channel:



2.5×10^{12} cm^{-2}

2.5×10^{12} cm^{-2}

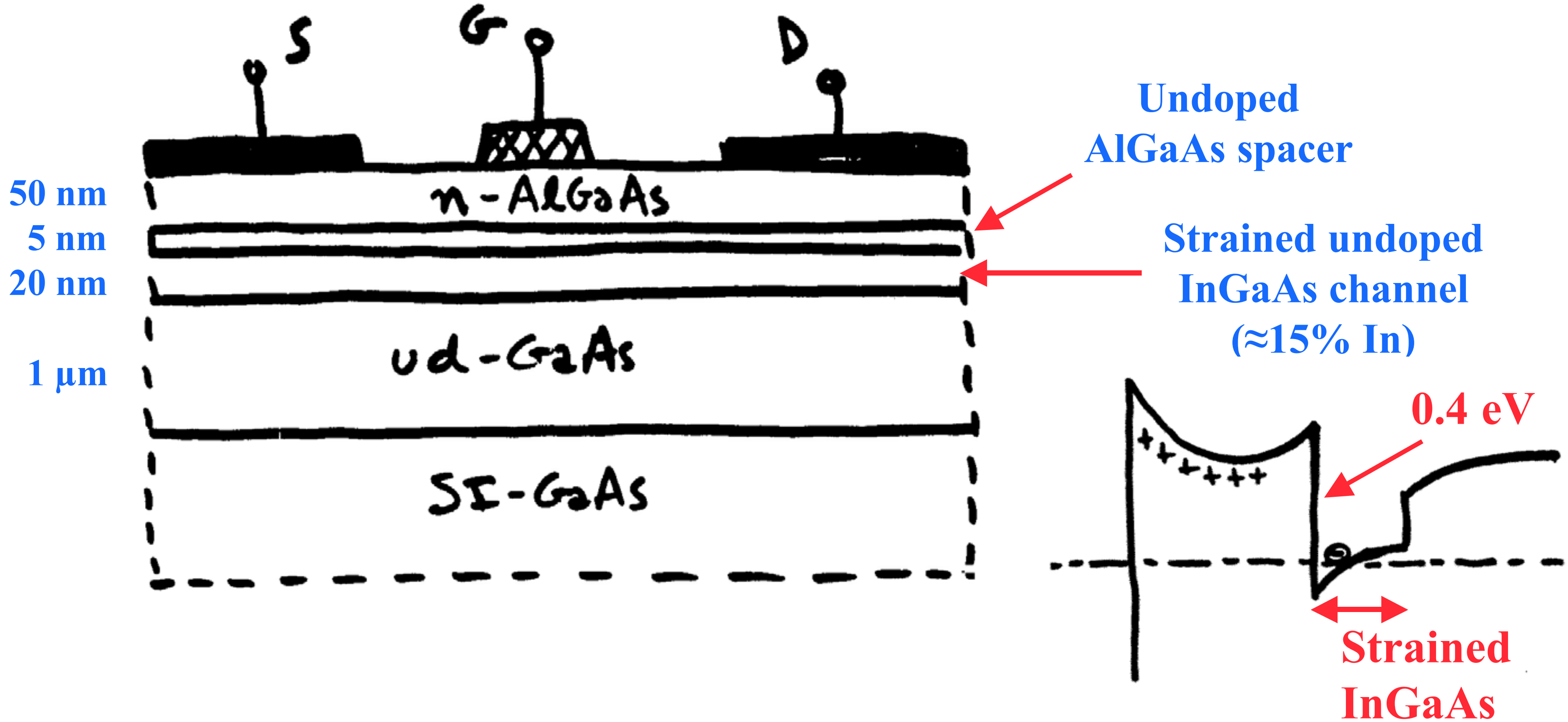
4×10^{12} cm^{-2}



Work of T. Kuo et al at MIT and AT&T Bell Labs

HEMTs - the pseudomorphic HEMT (PHEMT)

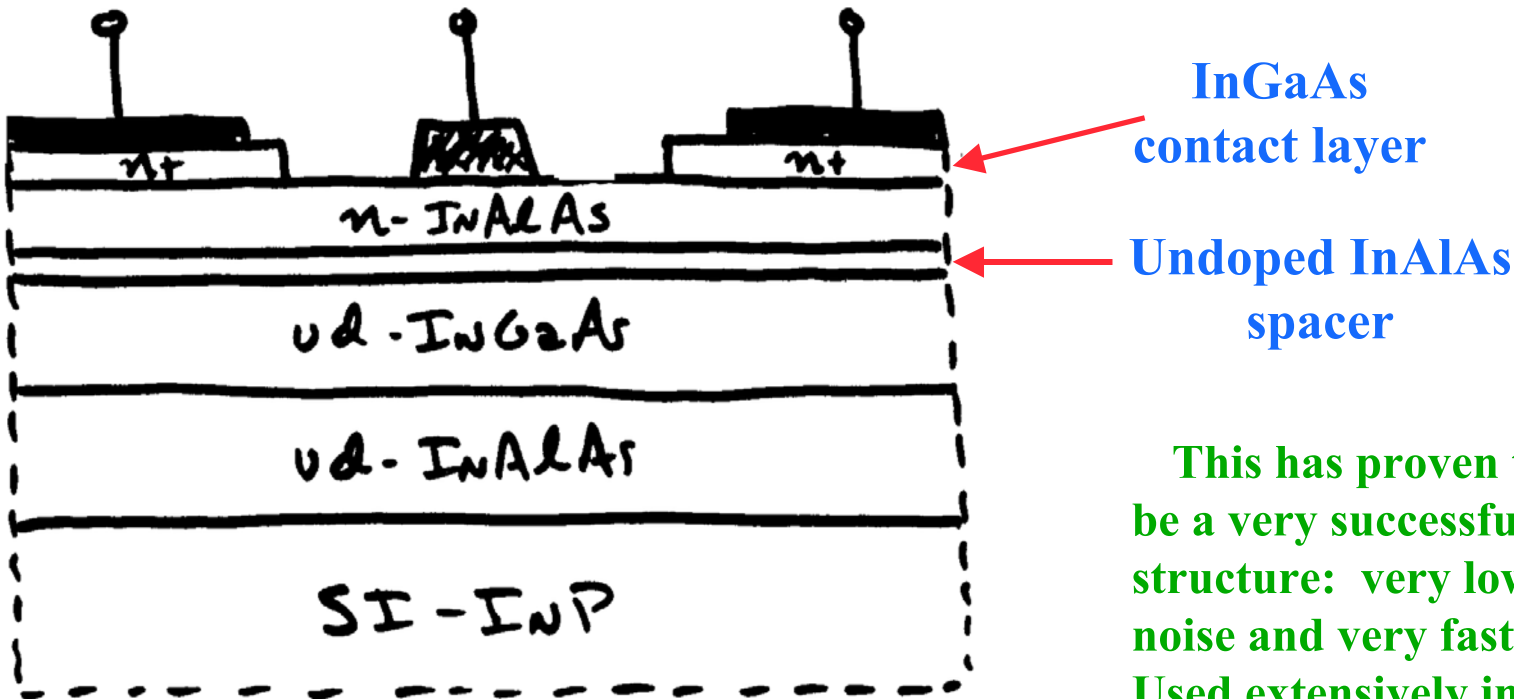
The problem of DX centers with high Al fraction layers led to the development of the pseudomorphic HEMT, or PHEMT:



This structure was first developed at the University of Illinois.

HEMTs - the InGaAs/InAlAs HEMT on InP

Another solution to the problem of DX centers in high Al fraction AlGaAs layers is to use the InGaAlAs system on InP:



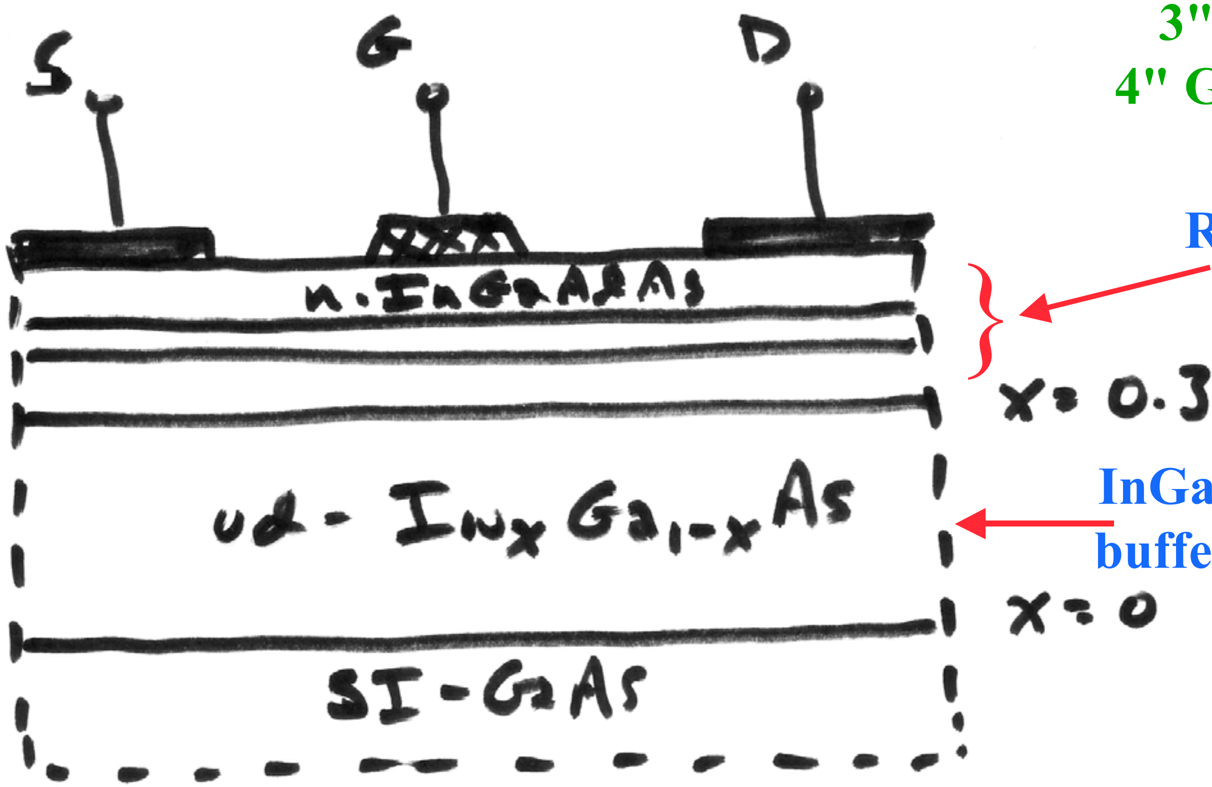
This has proven to be a very successful structure: very low noise and very fast. Used extensively in satellite receivers.

- 0.5 eV barriers
- no DX centers in InAlAs
- mobility and saturation velocity 50% higher than in GaAs

HEMTs - the Metamorphic HEMT (mmHEMT) on GaAs

A recent DX center solution that doesn't require expensive InP substrates is the metamorphic HEMT:

3" InP: $700
4" GaAs: $170



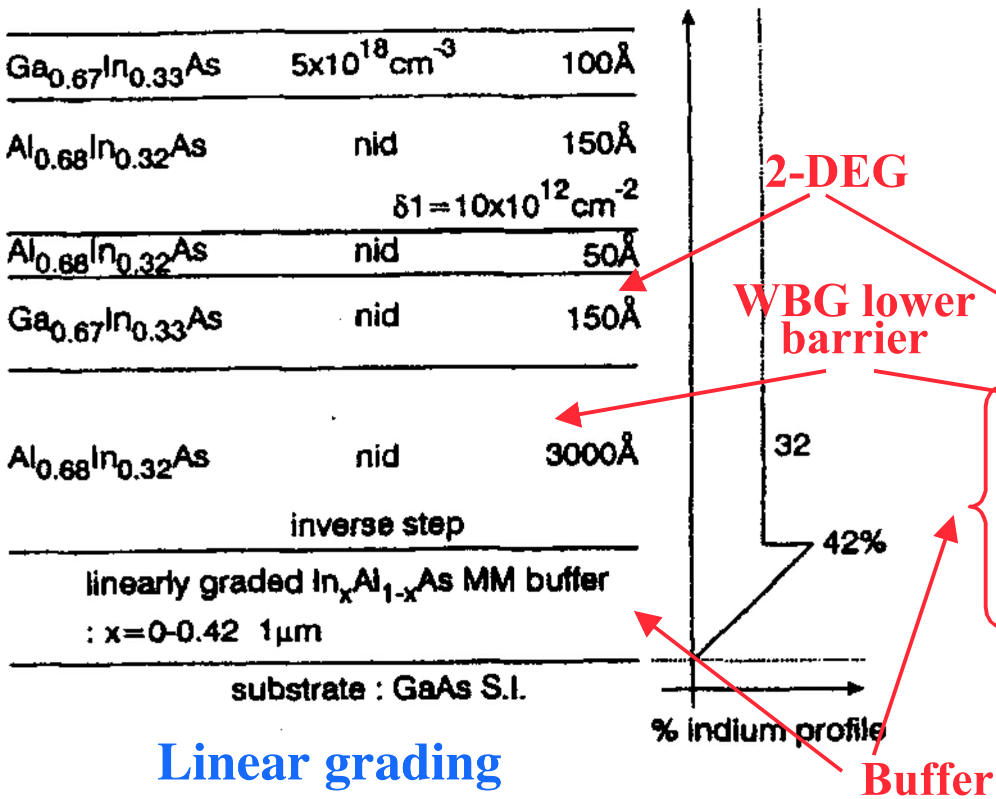
Relaxed device epilayers

InGaAs graded buffer (relaxed)

- we talked earlier about step and linear grading of such buffers
- the next question is: How high an In composition is optimal?

mmHEMTs - examples of relaxed graded buffer layers

(first seen in Lect. 4)



Linear grading

n^+	$In_{0.30}Ga_{0.70}As$	13 nm	5x10^{18}
i	$In_{0.29}Al_{0.71}As$	20 nm	
n^+	$In_{0.29}Al_{0.71}As$	30 nm	2x10^{18}
i	$In_{0.29}Al_{0.71}As$	4 nm	
i	$In_{0.30}Ga_{0.70}As$	40 nm	
i	$In_{0.29}Al_{0.71}As$	0.4 μm	
i	$In_{0.20}Al_{0.80}As$	0.2 μm	
i	$In_{0.10}Al_{0.90}As$	0.2 μm	
i	GaAs		

Step grading

- There is no general agreement on which approach is superior and the choice often one of convenience and/or practicality.
- Because the last layer is often not fully relaxed, it is common to grade to a certain level and then step back, as seen in the structure on the left. In this way a fully relaxed top structure can be realized.

mmHEMTs - what In fraction?

There is a trade-off between low field mobility and sheet carrier concentration in the channel:

(Image deleted)

See S. Bollaert et al, Ann. Telecommun., 56 (2001) 15-26.

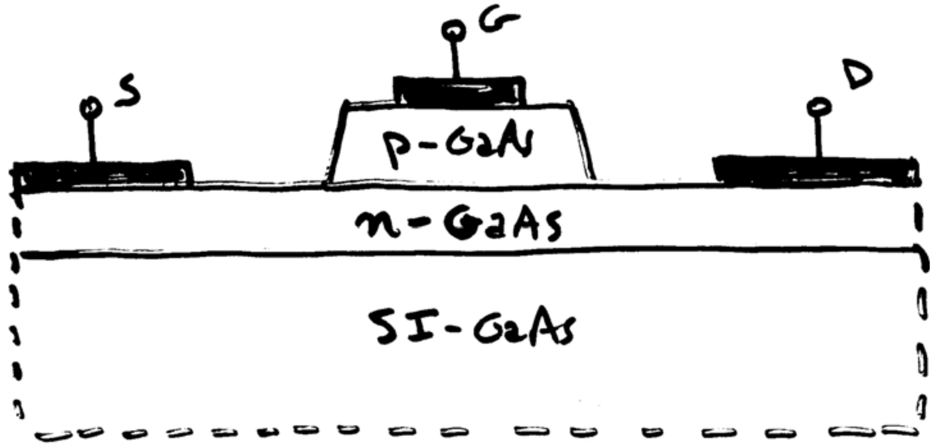
Conduction band barrier **Mobility vs. Sheet density**

- **the presently accepted "optimum" seems to be about 30% In**

Heterojunction FETs - JFET

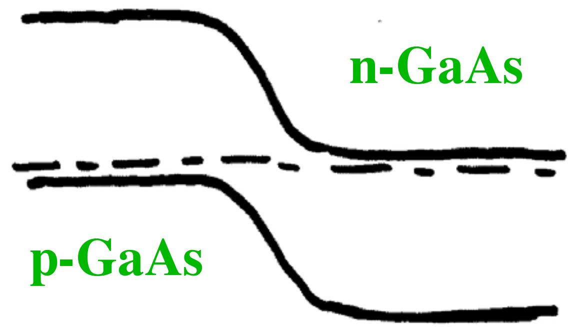
Structure:

- JFETs can be viewed as improved MESFETs with an oppositely doped layer having been inserted under the gate; it might even be wider bandgap



The gate performance is much improved:

- lower leakage
- larger forward turn-on voltage



Comments on JFETs:

- can be made both n- and p-channel
- gate lengths can be made as those of MESFETs
- requires making ohmic contacts to both n- and p-type
- only being pursued in small, low level efforts at several companies

FETs - Comparing the choices

- **Noise figure (right)**
- **f_T (below, left)**
- **f_{max} (below, right)**

(Images deleted)

See F. Schwierz, Microwave Transistors - The last 20 years.

- **Heterostructure devices are essential to get high speed and low noise**

HEMTs - Comparing the choices

- **Standard structure of a high speed HEMT**

- **Comparison of channel properties (mobility and sheet carrier density)**

(Images deleted)

See F. Schwierz, Microwave Transistors - The last 20 years.

HEMTs - Comparing the choices

- f_T for HEMTs on GaAs and on InP:

(Image deleted)

See S. Bollaert et al, Ann. Telecommun., 56 (2001) 15-26.

- InP-based HEMTs are faster than GaAs-based HEMTs
- The higher the indium fractions in the channel, the higher f_T

HEMTs - Comparing the choices

- **Output power and noise figure for HEMTs on GaAs and on InP:**

(Image deleted)

See S. Bollaert et al, Ann. Telecommun., 56 (2001) 15-26.

- **GaAs wins in power and cost, while InP is essential for low noise**

Current FET issues - power, high T semiconductors

- **Lower power applications such as cell phone**

(Image deleted)
See M. Golio and B. Newgard, IEEE, 2001.

- **Higher power applications and the need for high temperature semiconductors**
  - **Potential for transmitter cost reduction with the development of transistors offering higher power per package than available from Si.**

(Image deleted)

See R.C. Clarke and J.W. Palmour, SiC Microwave Power Technologies, Proc. IEEE 90 (2002) 987-992.

High-T semiconductors for FETs - materials options

- Some key properties of high-T materials of current interest, including thermal conductivity, $\mathcal{K}$, and breakdown electric field, E_c.

(Image deleted)

See R.J. Trew, SiC and GaN Transistors, Proc. IEEE 90 (2002) 1032-1047.

- Velocity verses field curves for important high-T semiconductors

Current FET issues - SiC and GaN FETs

- **SiC examples**

(Images deleted)

See R.C. Clarke and J.W. Palmour, SiC Microwave Power Technologies, Proc. IEEE 90 (2002) 987-992.

- **SiC MESFET (above)**
- **Static induction transistor, SIT - a vertical MESFET (right above)**
- **Ion-implanted SIT (right)**

Current FET issues - power, high T semiconductors, cont.

- **The high power device landscape:**

(Image deleted)

See R.J. Trew, SiC and GaN Transistors, Proc. IEEE 90 (2002) 1032-1047.