# Part 4: Heterojunction Devices

Heterojunction basics

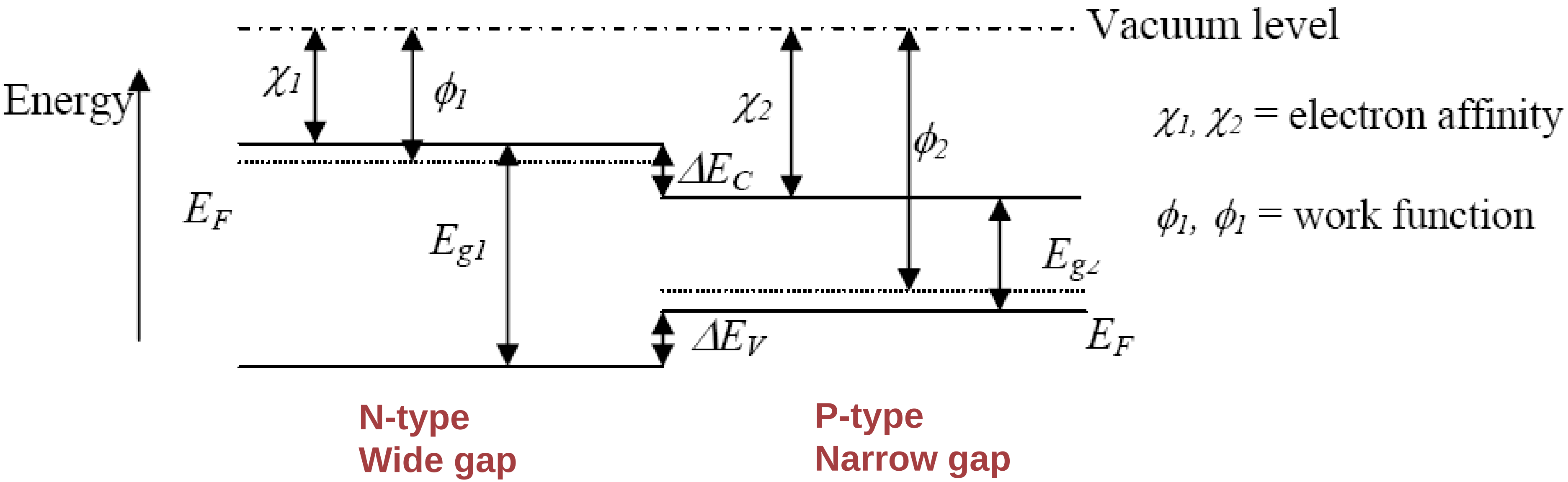
The High Electron Mobility Transistor (HEMT)

The p-HEMT and m-HEMT

# Heterojunctions

Consider an **n-p junction** formed from two materials of different band gap

Before contact




Semiconductors align according to their electron affinity (electronegativity) : related to the work function (but this is dependent on doping type). This will determine $\Delta E_C$ and $\Delta E_V$

# Heterojunctions

The total discontinuity is equal to the difference in band gap

$\Delta E_C + \Delta E_V = E_{g1} - E_{g2} = \Delta E_g$

In principle, $\Delta E_C = \chi_2 - \chi_1$ and could be found from book values. In practice $\Delta E_C$ and $\Delta E_V$ have to be measured as their estimates are often not accurate.

Discontinuities can be described in different ways. One common way is to just quote the split between conduction and valence bands ie: '60% Conduction band discontinuity' or '60/40 split'

e.g: GaAs- AlGaAs is well known to have a 60/40 CB/VB split

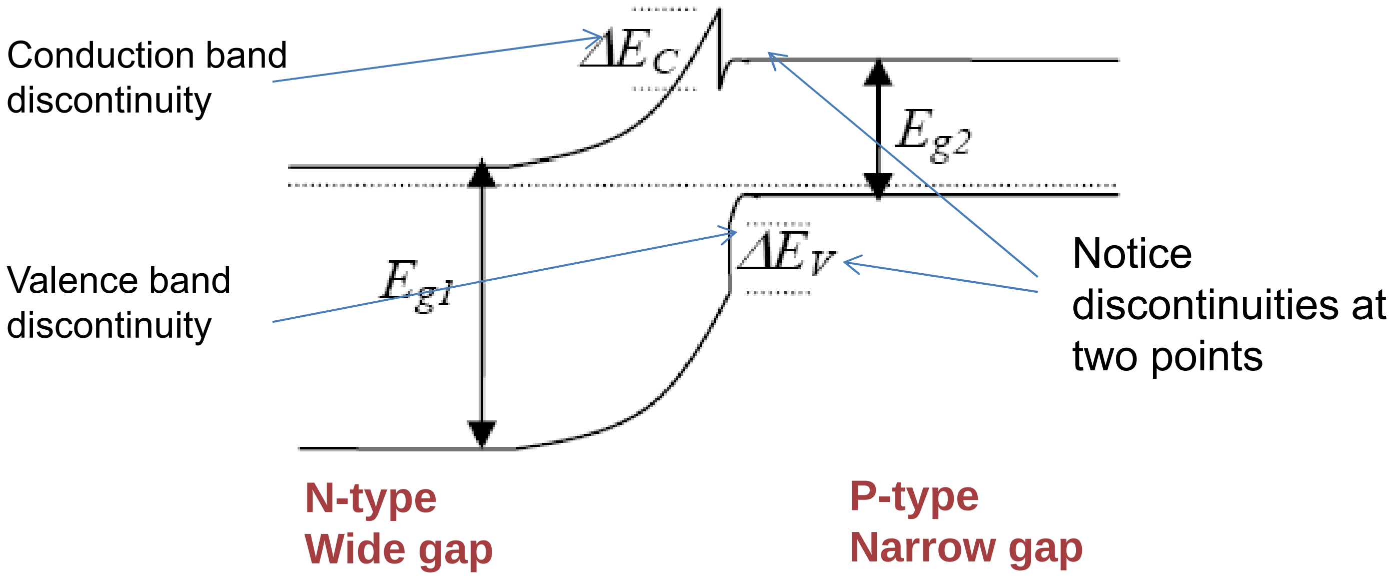
GaAs- $E_g$=1.42eV $Al_{.3}Ga_{.7}As$= $E_g$=1.90eV, so $\Delta E_g$=0.48eV

so $\Delta E_C$= 0.29eV, $\Delta E_V$=0.19eV

# Heterojunctions

After contact

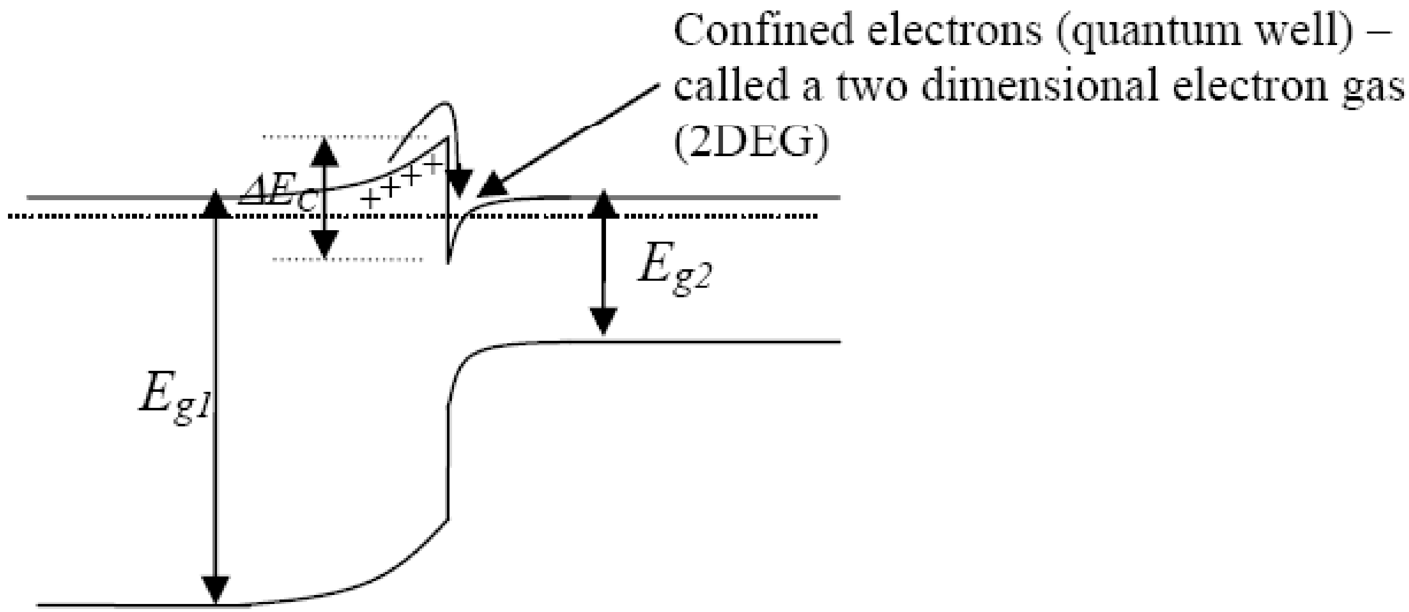
Charge flows into the narrow gap material, equalising the Fermi level. Pushes up the narrow gap energy levels.




Here we have reduced the barrier for electrons coming from the n-type material (left) compared to the barrier for holes.

# Heterojunctions

What about an n$^+$-n heterojunction?




Here electrons accumulate on the lower bandgap side of the junction in a concentrated 'spike'. We call this a two-dimensional electron gas (2DEG)

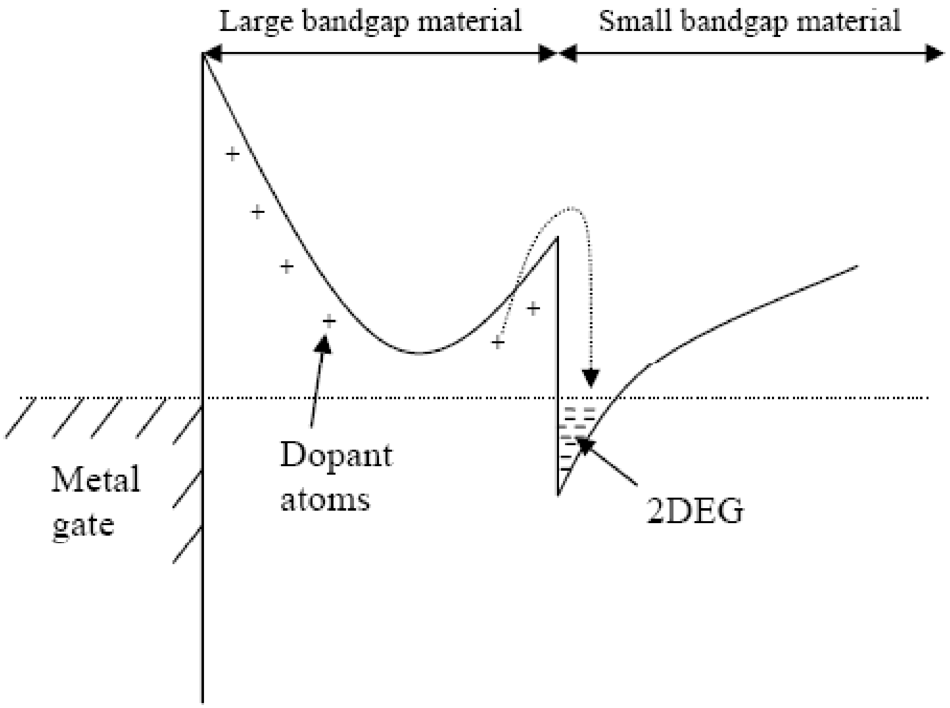
# Heterojunctions

The 2DEG is the basis of the so-called high electron mobility transistor (HEMT), also occasionally called the heterojunction FET (HFET).

The operating principle of the HEMT is quite similar to the MESFET, but the channel formation is different

Electrons from dopant atoms in the large bandgap material & close to the heterojunction transfer to form the 2DEG

These electrons are then separated in space from their ionised donors



# HEMT


Why is this useful?

Ionised impurity scattering is one of the main contributors to reduced mobility in semiconductors

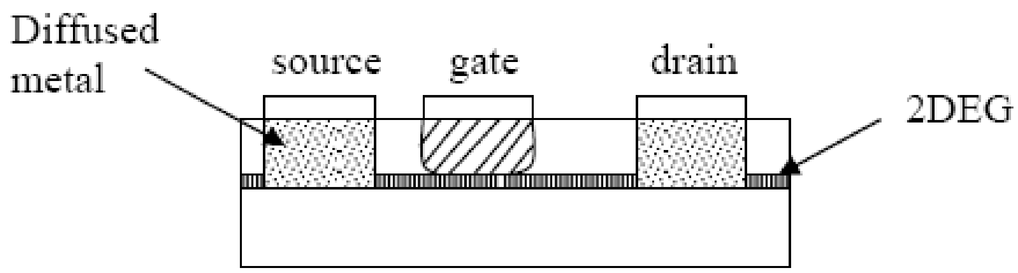
As a result of spatial separation in the HEMT scattering due to ***ionised impurities*** is greatly reduced. As a result- ***the mobility is increased***.

Note that electrons can move unrestricted into the paper on the band diagram and this forms the channel (i.e. between the source and the drain). The channel forms at zero gate bias by depletion from the large bandgap material. The channel can be depleted through application of a gate voltage, so this is a depletion mode device like the MESFET.

# HEMT

The practical device layout is very similar to a MESFET

The device characteristics, calculation of $I_D$, $g_m$ ,$f_T$ etc are also similar to that of the MESFET




If we remove ionised impurity scattering then what is left to restrict the mobility?

**Alloy scattering-** use elemental of binary channel materials, eg: Si, GaAs

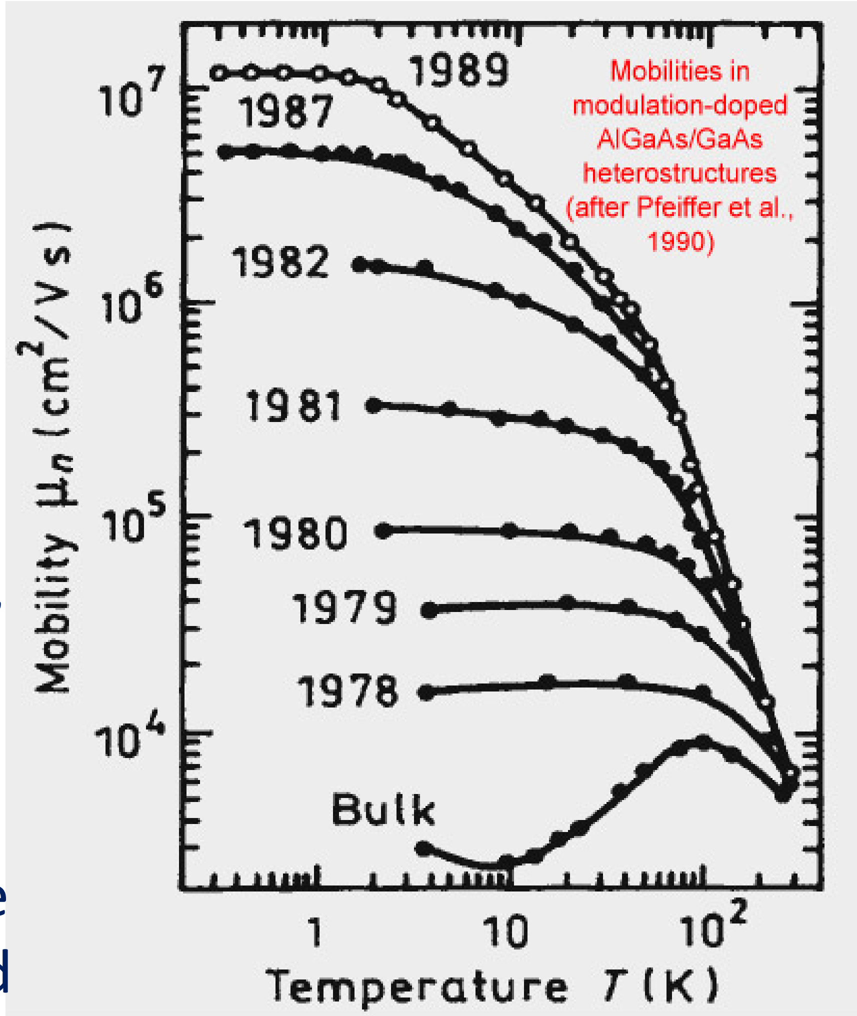
**Defects**- require very high quality materials and interfaces

What then is left is **phonon scattering** (temperature related)

# HEMT

2DEGs offer extremely high mobility electrons, especially when cooled to remove phonon scattering.

e.g: for GaAs/AlGaAs at 4K mobilities ~10,000,000cm$^2$/Vs have been measured. The room temperature mobility can still be up to 300,000cm$^2$, which is 100x the bulk GaAs value




2DEGs have been a test bed for fundamental quantum physics e.g: the quantum Hall effect was first observed in a 2DEG and took the Nobel Prize for physics in the 1980's.

# HEMT

**Advantages of HEMT over the MESFET**

- $g_m$ and $f_T$ are improved due to enhanced mobility
- $g_m$ increased due to the 2DEG being close to the gate giving good gate control
- $g_m$ is more constant with $V_G$ because the channel is confined in a small space

Recent results; GaAs/AlGaAs HEMT : $f_T \sim 500\ GHz$

<u>Applications</u>

High frequency amplifiers (satellite TV), RF power amplifiers and switches (mobile phone handsets)

# p-HEMT and m-HEMT

Consider the channel materials which would be possible to combine with GaAs substrates.

| Material | Lattice Constant | |
|---|---|---|
| AlAs | 0.566nm | +0.2% |
| GaAs | 0.565nm | |
| InAs | 0.606nm | +7.2% |
| InSb | 0.648nm | +14.6% |

**Note: larger lattice constant-> lower band gap, higher mobility**

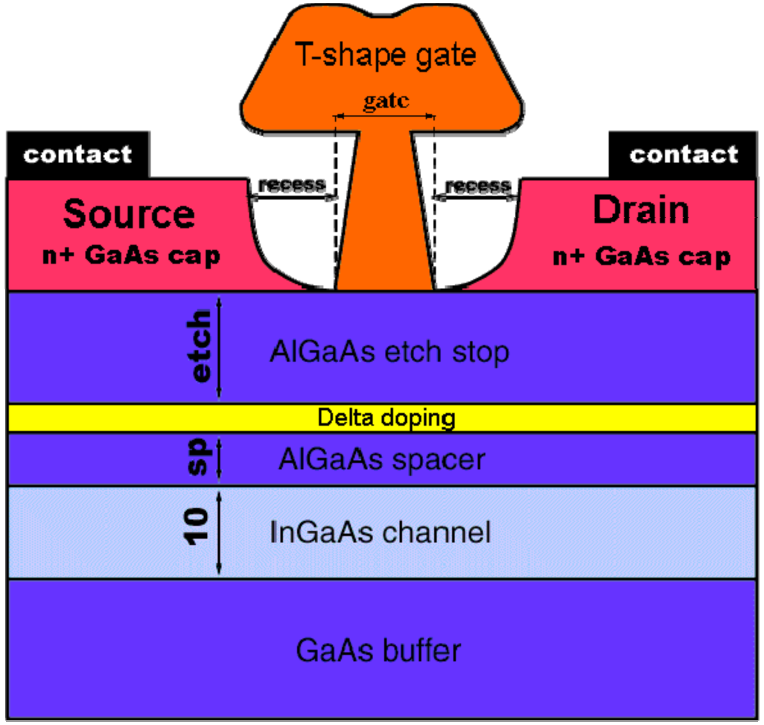
AlAs is very close to the lattice constant of GaAs. OK to grow AlAs, or $A_{lx}Ga_{1-}xAs$ on GaAs.

Would be beneficial to move to InAs channels. However InAs has a 7% larger lattice constant than GaAs. If grown on GaAs this would put a 7% compressive strain on the InAs, which is too high and result in relaxation (dislocations).

Mixed with GaAs to form $In_xGa_{1-x}As$ however, it would be possible to grow ultrathin layers of on GaAs providing the thickness and strain is low.

# p-HEMT and m-HEMT

This is the concept behind the pseudomorphic HEMT. Here providing the low gap channel is thin enough we need not use precisely lattice matched materials but can instead allow a degree of mismatch

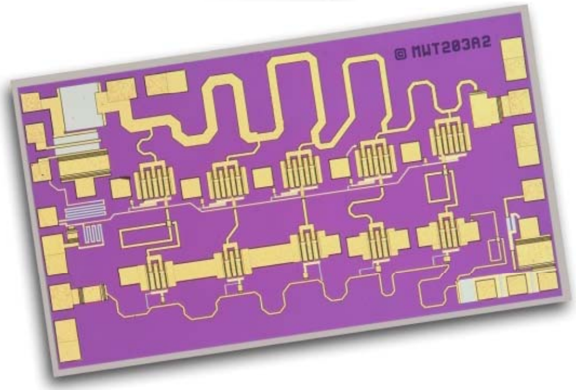



Examples of this include using InGaAs instead of GaAs in a GaAs/AlGaAs HEMT or using InGaN as the channel in a GaN/AlGaN HEMT. In each case the In containing material is lower gap and higher mobility than its replacement.

HEMTS also use *delta doping*- 2D sheet of dopants deposited using a special technique

# p-HEMT and m-HEMT

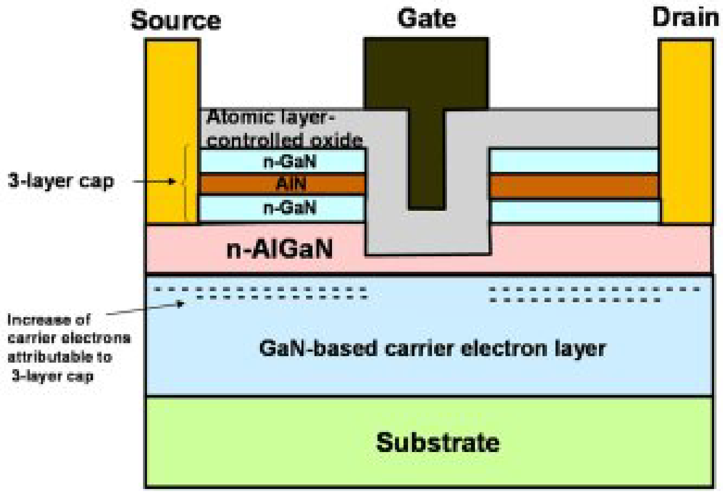

HEMTs are the basis for many microwave circuits, either on special PCB boards or as monolithic microwave integrated circuits (MMICs)



Functions include microwave mixing, power amplification, low noise amplification, and high frequency switching. Inputs and outputs on MMIC devices are frequently matched to a characteristic impedance of 50 ohms.


The most common consumer devices are GaAs-based low noise amplifiers (LNAs) and RF switches in mobile phones.

# p-HEMT and m-HEMT



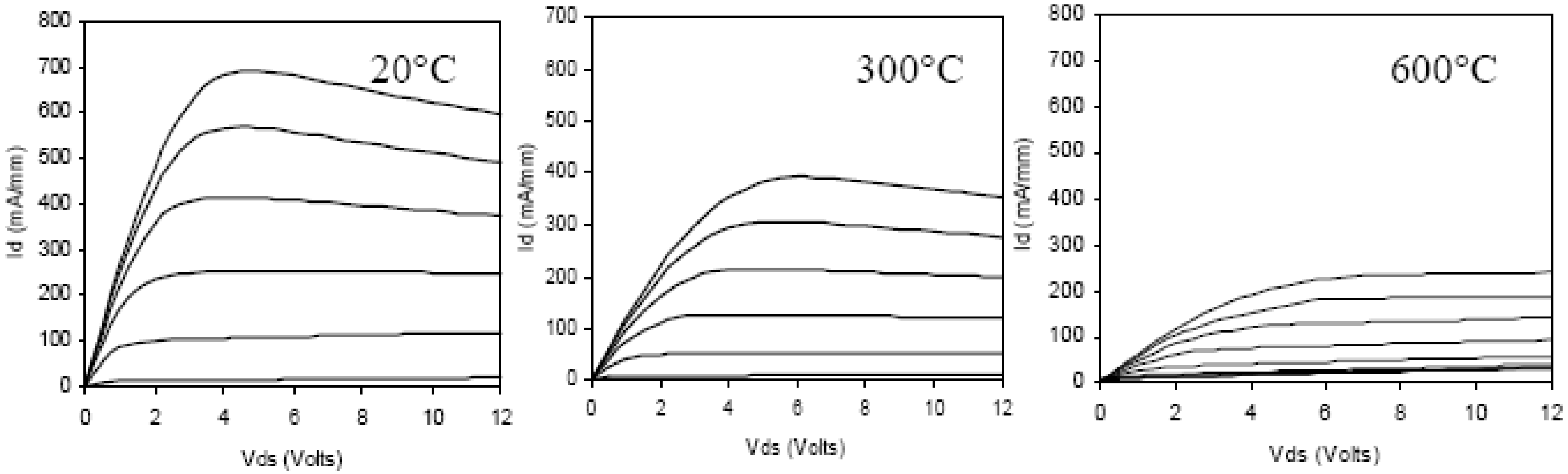

AlGaN/GaN HEMTs are now becoming popular for RF power applications (eg: mast power amplifiers for mobile networks), airborne RADAR). This is due to the high voltages possible and high temperature capability.

GaN has a wide band gap or 3.3eV which allows for higher breakdown voltages.


These devices have demonstrated a power output of 30 W per mm of gate width, which is an improvement of ~ 30 times over the power densities possible with GaAs/AlGaAs HEMTs.

# p-HEMT and m-HEMT

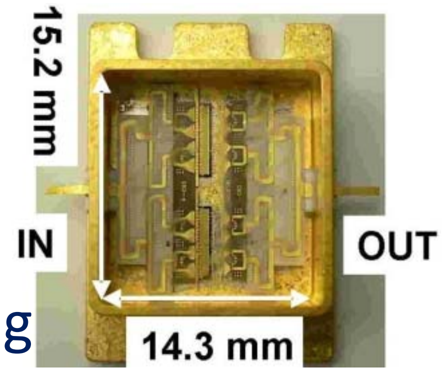
## AlGaN/GaN HEMT – high temperature demonstration




Usable characteristics even at 600$^{o}$C, which is not the case for Si and GaAs (limit ~100$^{o}$C).

These devices are suitable for high temperature and high power dissipation environments.

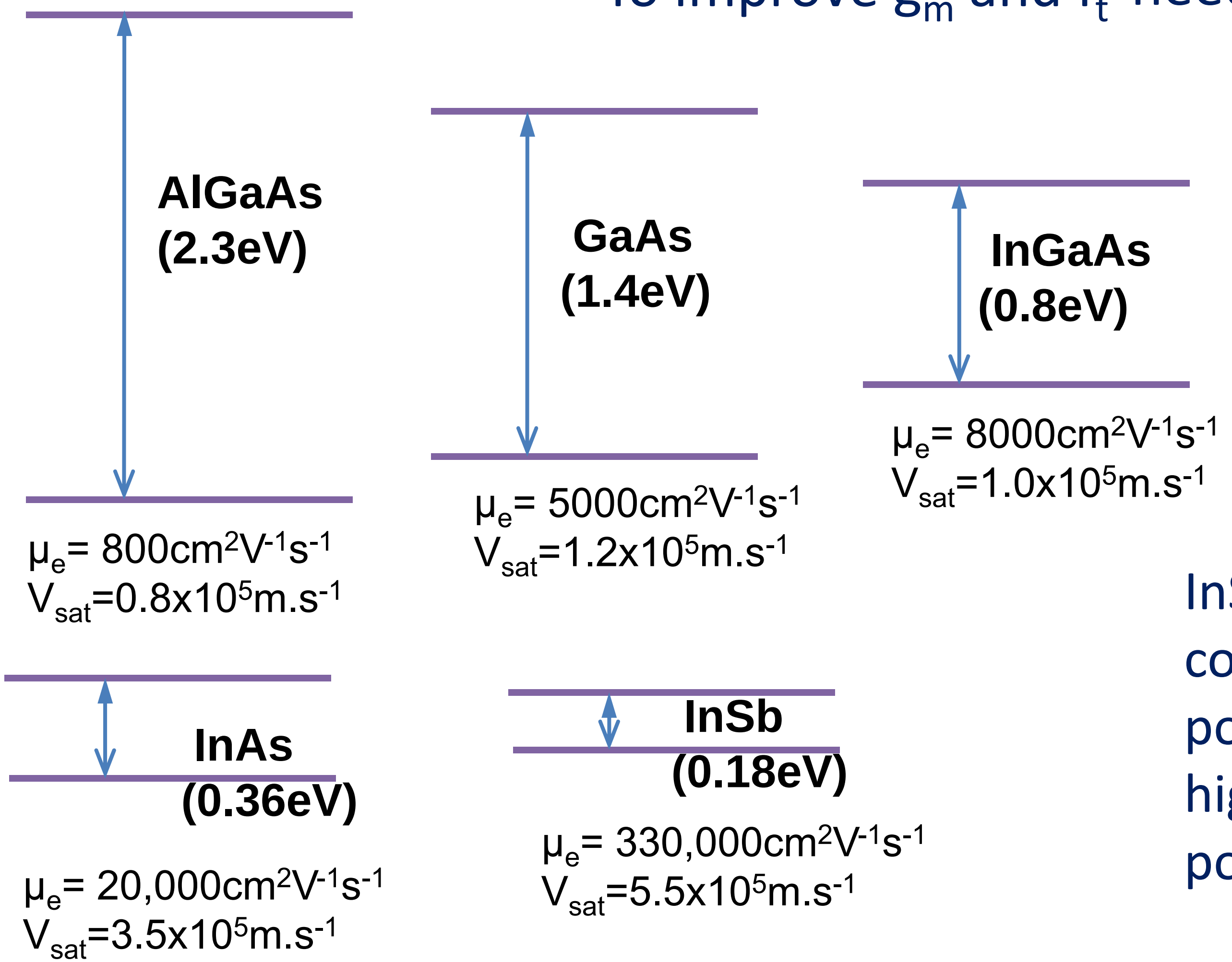
As well as discrete devices, GaN MMICs also emerging



# p-HEMT and m-HEMT

## HEMT trends –GaAs based

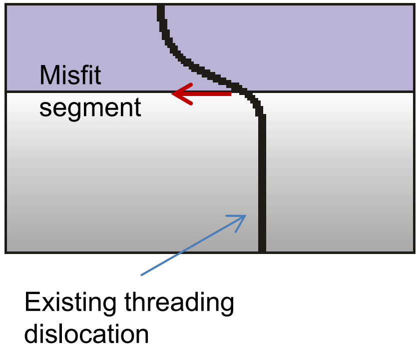
To improve $g_m$ and $f_t$ need high μ and $V_{sat}$




InSb has considerable potential for ultra high-speed, low power devices

# p-HEMT and m-HEMT

If we increase the mismatch we run into the problem of strain relaxation. This relaxation takes place through dislocations (crystal faults)




Models which describe how a thin layer relaxes do so by comparing the energy required to 'bend' a dislocation with the strain energy. The bend in the dislocation represents misfit

An important term which is used is the Critical Layer Thickness (CLT) . This describes the maximum thickness which can be sustained for a thin mismatched layer without forming dislocations.

A good rule of thumb for the CLT is 0.8nm/strain($\varepsilon$).

# p-HEMT and m-HEMT

Consider a HEMT with an $In_{.2}Ga_{.8}As$ channel. This can be considered as 20% InAs and 80% GaAs and has a commensurate lattice constant. The value of its strain to GaAs is 1.4% (ε=0.14) and the CLT value is therefore about 50nm.

This thickness is sufficient to create a usable channel. The device is called a **pseudomorphic HEMT (pHEMT)**

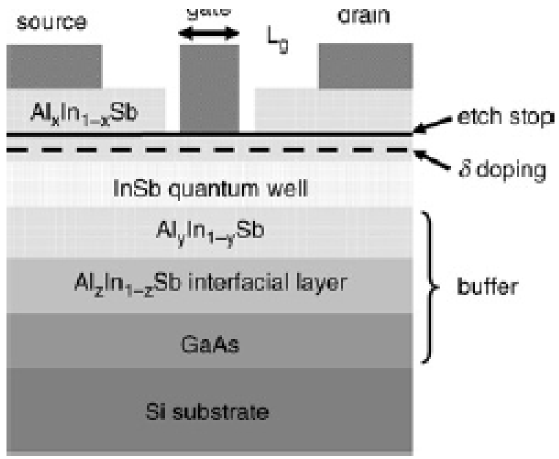
It would be useful to use higher In fractions in the $In_xGa_{1-x}As$ as the mobility increases with increasing indium fraction, or to use materials like InSb with even higher mobilities. However the mismatch is too high.

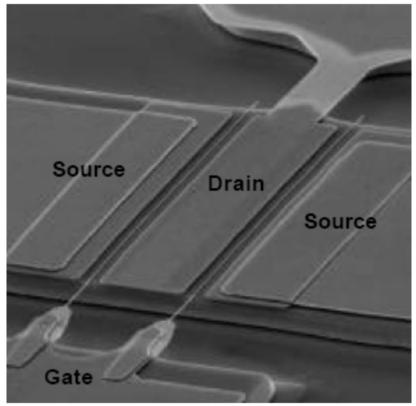
One approach around this is to relax the whole structure. We grow a thick layer of In-containing strained material and allow this to relax to increase the lattice constant.

# p-HEMT and m-HEMT

This approach is called a **metamorphic HEMT (mHEMT).** The mHEMT approach has been used to grow InAs or InSb channels on GaAs.

More recently it has been used to grow InSb channels on Silicon with a 19% lattice mismatch




The major problem with the mHEMT is controlling the effect of the dislocations coming from the relaxed buffer layer.

Another issue common to all approaches using narrow channels is low breakdown voltages. This can limit the potential power output.