Other types of FETs

- Si is the dominant semiconductor just because of the excellent Si/SiO₂ interface. So far, this is the best semiconductor/dielectric interface.
- But Si is inferior to many other semiconductors (e.g. GaAs, InSb, etc) in terms of μ, Vₜₚ.
- RF, microwave, millimeter wave applications need faster transistors.
- But MOSFETs are not that good with those materials due to the lack of a good semiconductor/dielectric interface.
JFETs usually work in depletion mode (normally on). Enhancement mode (normally off) devices are desired for switches.

Why do we need a p substrate here?

\( V_{GS} < 0 \Rightarrow \text{depletion region widens.} \)

At some point, the channel is off?
GaN Die Model from manufacturer

For thermal simulation

\[ \text{GaN\_LTspice\_GS-065-060-2-D\_L3V4P1} \]

**Ids vs. Vgs Characteristic**

\[ I_{DS} \text{ vs. } V_{GS} \]  

**Ids vs. Vds Characteristic (25 °C)**

\[ I_{DS} \text{ vs. } V_{DS} \text{ @ } T_j = 25 \degree C \]
MESFET

compare to MOSFET, no self alignment

n-channel

\[ V_G = 0 \]
Will you have an inversion layer here?
I - V Characteristics

For larger (more positive) $V_D$, $V_G$ more negative than $V_{GS} \Rightarrow$ depletion region wider on the $D$ side.
High $V_D$, pinch-off
Saturation

$V_G = 0$
$V_D$

"Normally on"
JFETs & MESFETs are "normally on". Channels are doped. Turn them off by depleting them.

Dopants scatter carriers. We want \( \mu \) & \( V_{to} \) as high as possible.

(What's the mobility of a typical Si MOSFET?)

Solution: MODFET.

Many names: HEMT, HFET.
Solution: MODFET. Many names: HEMT, HFET.

Want electrons ($n$) but not dopants ($N_d$).

The idea: Have $N_d$ in one layer. But get $n$ in another.

2-dimensional electron gas (2DEG)
Space charge (ionized donors) in AlGaAs **barrier layer** resulting from **electron transfer**

$E_{\text{vac}}$
Electrostatic potential distribution as a result of Poisson’s equation (Gauss’s law) and carrier statistics, similar to (but more complicated than in a simple Schottky or junction)

Parasitic channel

2-dimensional electron gas (2DEG)

\[ \Delta E_c = \chi_2 - \chi_1 \]
An undoped spacer layer is grown before the n doped AlGaAs layer, to separate ionized dopants from channel.

$V_G = 0$, Fermi levels line up.

2-dimensional electron gas (2DEG)
(not to scale)
Now, $V_G < 0$

Can there be an inverted p channel in AlGaAs?

Negative charge (electrons) partition between 2DEG and gate.
Now, more negative $V_g$, channel depleted.
To avoid "parasitic channel" in AlGaAs, can do "delta doping"
When the channel is totally depleted
To really understand MODFETs, we need to understand heterojunctions.

- Fabrication of heterostructures: epitaxy

![Diagram of lattice match and epitaxy](https://www.tf.uni-kiel.de/matwis/amat/semitech_en/kap_3/backbone/r3_4_1.html)

(Lattice match: $a_A \approx a_B$)

(Epitaxy may be homoepitaxy, e.g., undoped GaAs on semi-insulating GaAs in our MODFET example)

![Comparison of lattice structures](https://www.sciencedirect.com/science/article/pii/S0039602801015254)

$$a_A \approx a_B$$
Fig. 12.6. Bandgap energy and lattice constant of various III–V semiconductors at room temperature (adopted from Tien, 1988).
How do energy levels line up at interfaces?

There are no simple theories.

Pretty much every interface (even the same pair of materials but opposite growth order) needs to be experimentally determined.

Recently, first-principles calculations become able to predict.

For simple descriptions, there are two “rules” that are not obeyed.

Details (chemistry) of interface ignored, therefore no interface dipoles $\Rightarrow$ no discontinuity in electrostatic potential, or $E_{\text{vac}}$.

We followed this rule when analyzing the MODFET example.

In this illustration, the horizontal dimension is not meaningful except marking the interface; charge transfer dictates band bending.
Valence band max largely determined by anion atomic orbitals.

Both “rules” ignore interface dipoles.