Lecture 12b

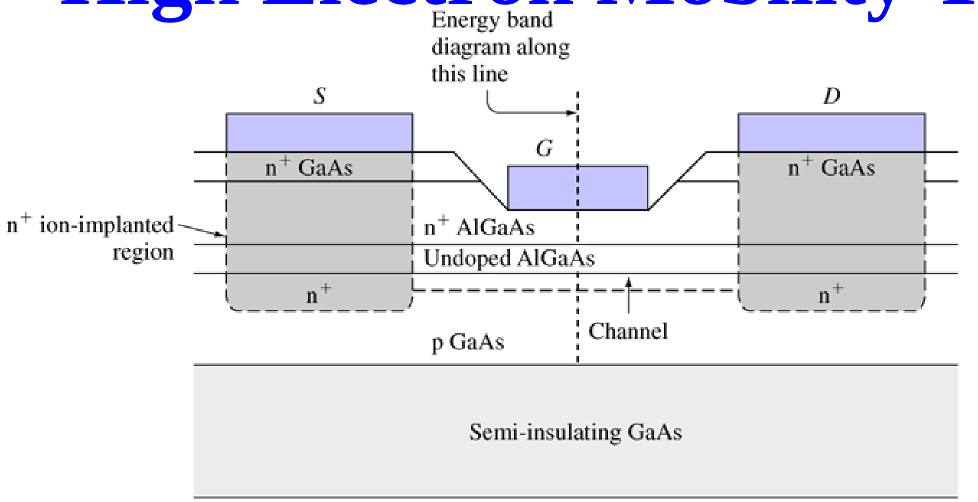
Advanced Field Effect Transistor (FET) Devices

Reading:

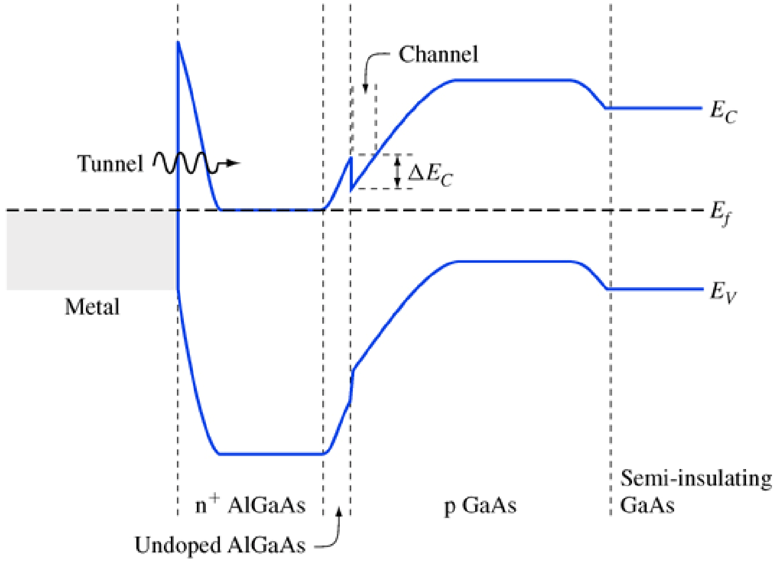
(Cont'd) Notes and Anderson^2 Chapter 8.11

Some images from Anderson and Anderson text

Advanced Devices: FET Devices
High Electron Mobility Transistor (HEMT)



(a)



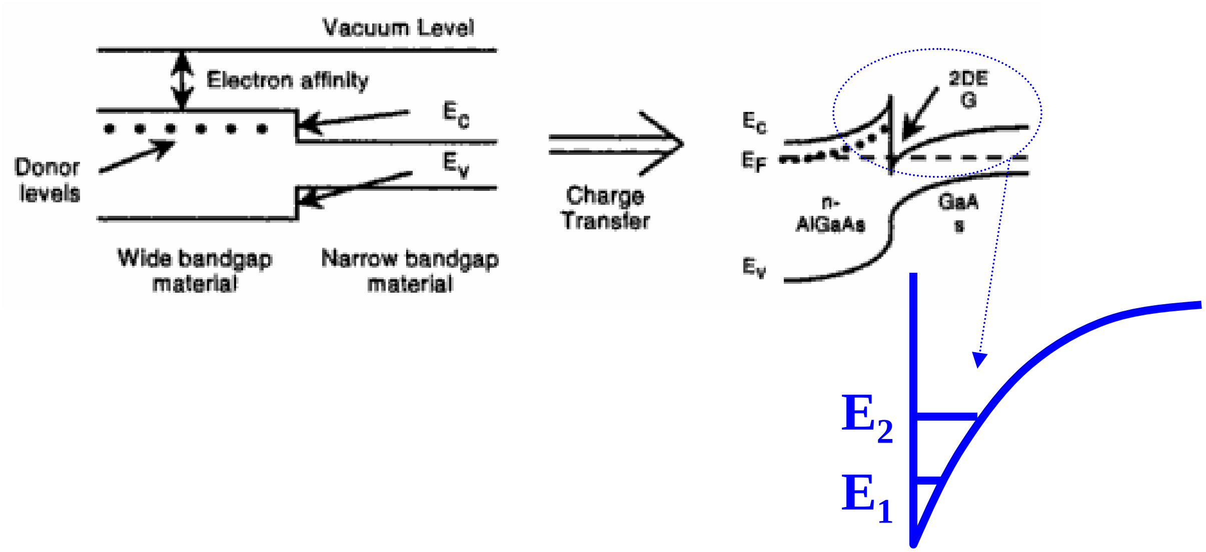
(b)

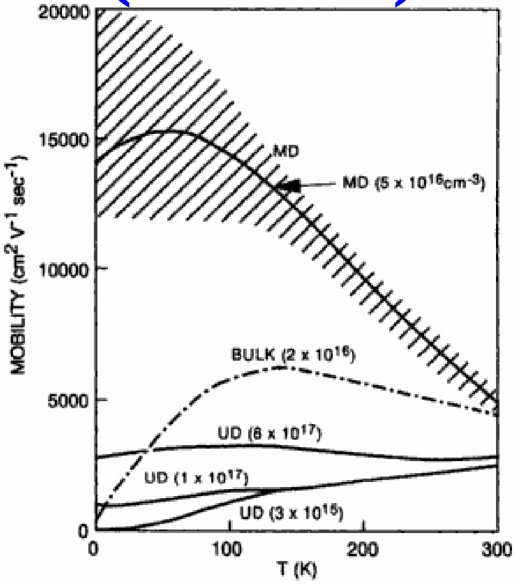
The cross-sectional schematic (a) of a GaAs-based Heterostructure Field Effect Transistor (HFET) or High Electron Mobility Transistor (HEMT) and (b) the energy band diagram normal to the gate.

The Schottky barriers at the metal-AlGaAs and metal-GaAs interfaces are thin enough to be of low resistance because of tunneling.

Doping is removed from the channel increasing mobility significantly.

Advanced Devices: FET Devices
High Electron Mobility Transistor (HEMT)



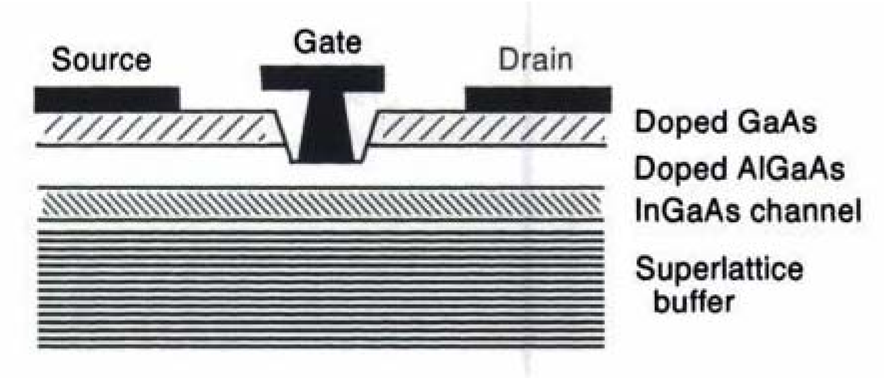


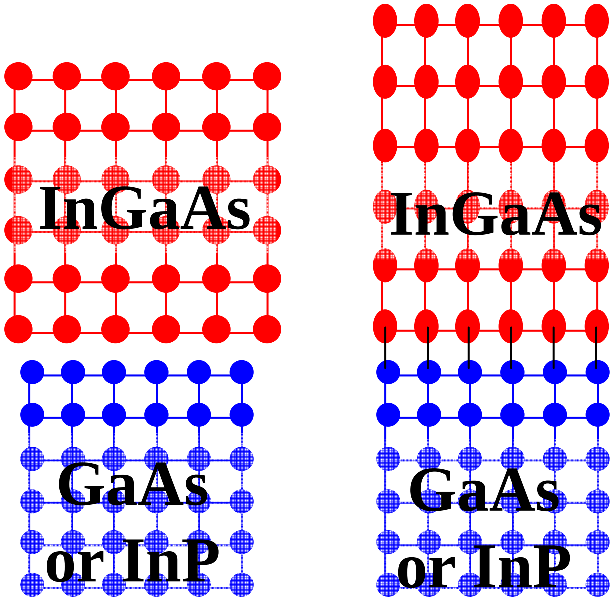
The channel is a 2D electron gas contained in the triangular quantum well created by the ΔEc of the AlGaAs-GaAs heterojunction. Also known as a MODFET, HFET, TEGFET, SDHT.

Advantages:

- **The mobility is not degraded by surfaces or interfaces like in a MOSFET. The AlGaAs-GaAs interface is lattice matched and thus has ZERO interface states.**
- **In a 2D electron gas (channel) the electron scattering is reduced by a factor of approximately $x^{2/3}$ making the mobility higher than in bulk. Some of this increase is due to separation of the dopants from the channel (modulation doping) and a small additional enhancement is due to the quantum 2D nature of the channel.**
  - **Example: Bulk GaN μ~1000-1200 cm^2/V-Sec but in an AlN/GaN channel, μ~2000 cm^2/V-Sec .**
- **The device is very fast because the channel thickness can be very precisely controlled (minimized) making the channel easy to deplete with a small gate voltage.**

Advanced Devices: FET Devices
Pseudomorphic High Electron Mobility Transistor (PHEMT)





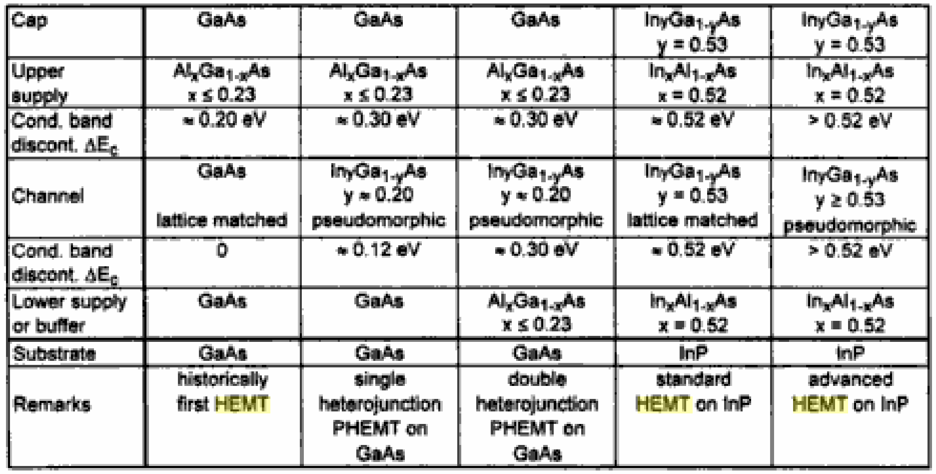
The channel is a a strained lattice 2D electron gas contained in the triangular quantum well created by the ΔEc the AlGaAs-InGaAs heterojunction.

Advantages:

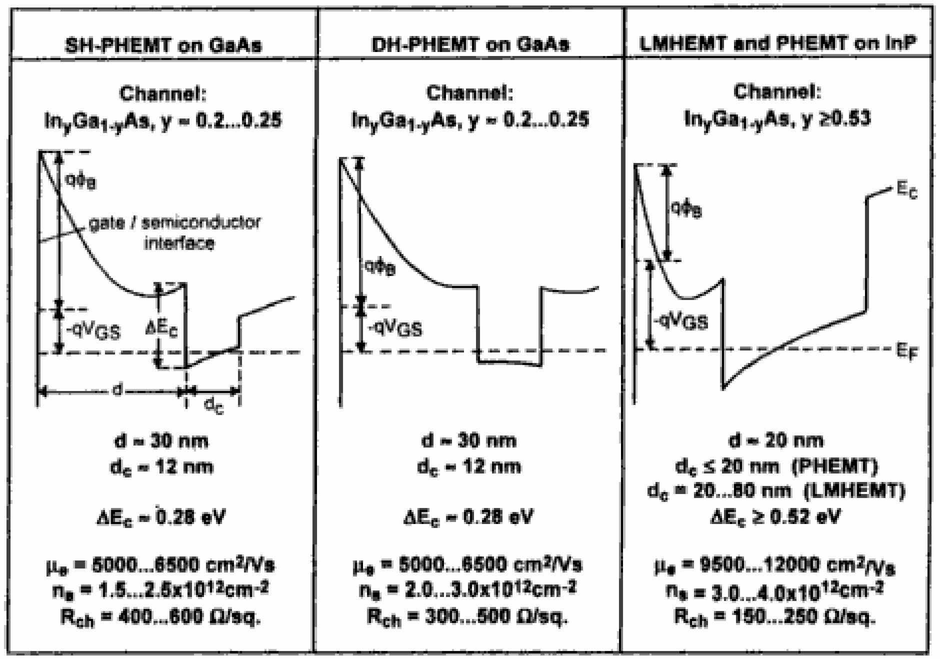
- **Higher channel charge (higher conductivity) due to a higher ΔEc for InGaAs vs GaAs Channels**
- **Higher saturation velocity of InGaAs results in higher frequency operation**
- **Lower Noise.**
- **Higher mobility of InGaAs results in smaller parasitic resistances and higher low field electron velocity. InGaAs μ~12,000 cm^2/V-Sec. In is typically 15-20% and Channels are typically 11-15 nm.**
- **The device is very fast because the channel thickness can be very precisely controlled (minimized) making the channel easy to deplete with a small gate voltage.**

Advanced Devices: FET Devices
Pseudomorphic High Electron Mobility Transistor (PHEMT)

- Single Heterostructure, Double Heterostructure and Advanced InP based HEMTS offer increased performance gains due to engineering the channel differently.
- Primarily one tries to minimize the channel sheet resistance, R_{ch} by increasing electron density and mobility.
- Having larger Dec as found in the higher In-content InGaAS on InP helps with noise and linearity since the channel charge is confined better.

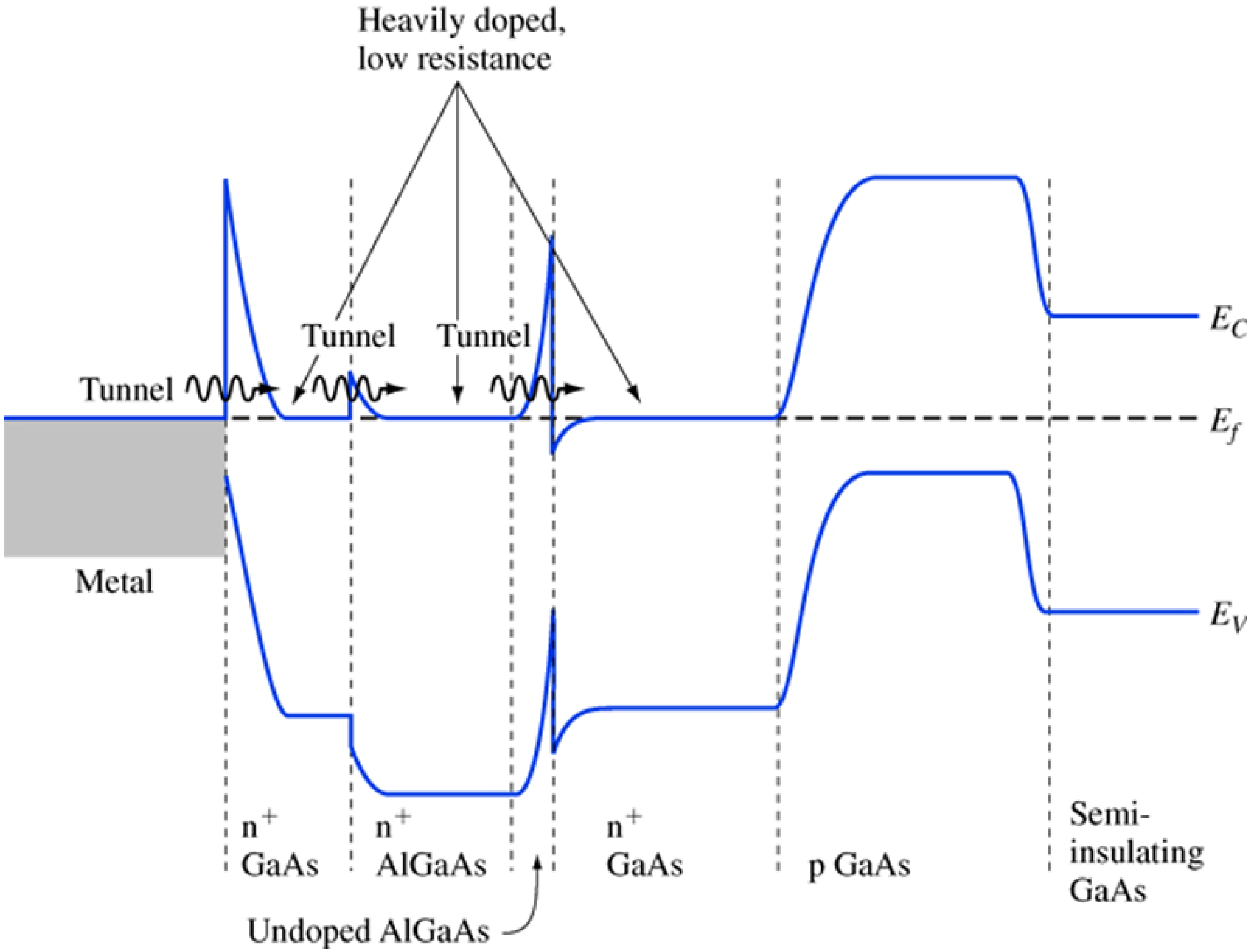


Cap	GaAs	GaAs	GaAs	$In_yGa_{1-y}As$ $y = 0.53$	$In_yGa_{1-y}As$ $y = 0.53$
Upper supply	$Al_xGa_{1-x}As$ $x \le 0.23$	$Al_xGa_{1-x}As$ $x \le 0.23$	$Al_xGa_{1-x}As$ $x \le 0.23$	$In_xAl_{1-x}As$ $x = 0.52$	$In_xAl_{1-x}As$ $x = 0.52$
Cond. band discont. ΔE_c	≈ 0.20 eV	≈ 0.30 eV	≈ 0.30 eV	≈ 0.52 eV	> 0.52 eV
Channel	GaAs lattice matched	$In_yGa_{1-y}As$ $y \approx 0.20$ pseudomorphic	$In_yGa_{1-y}As$ $y \approx 0.20$ pseudomorphic	$In_yGa_{1-y}As$ $y = 0.53$ lattice matched	$In_yGa_{1-y}As$ $y \ge 0.53$ pseudomorphic
Cond. band discont. ΔE_c	0	≈ 0.12 eV	≈ 0.30 eV	≈ 0.52 eV	> 0.52 eV
Lower supply or buffer	GaAs	GaAs	$Al_xGa_{1-x}As$ $x \le 0.23$	$In_xAl_{1-x}As$ $x = 0.52$	$In_xAl_{1-x}As$ $x = 0.52$
Substrate	GaAs	GaAs	GaAs	InP	InP
Remarks	historically first HEMT	single heterojunction PHEMT on GaAs	double heterojunction PHEMT on GaAs	standard HEMT on InP	advanced HEMT on InP



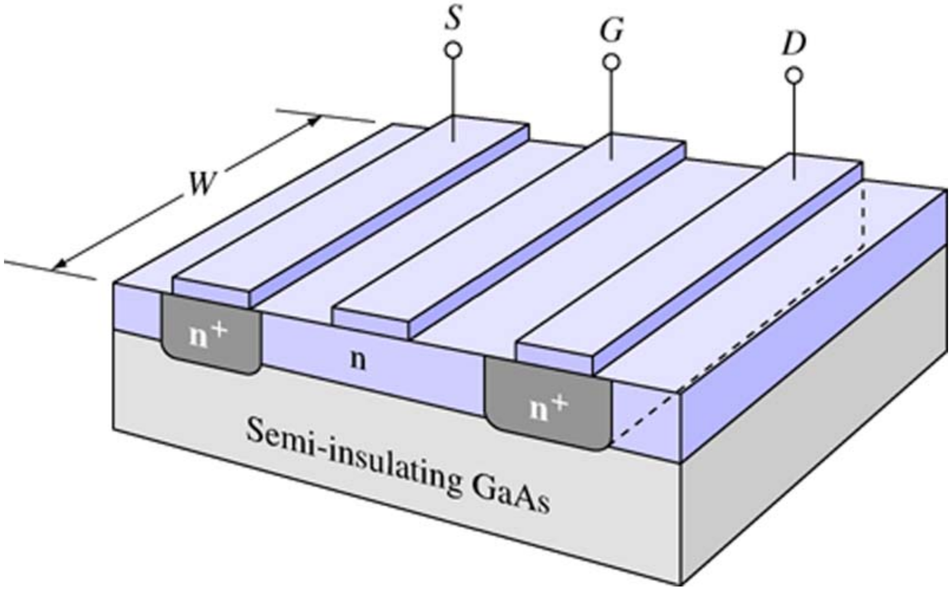
SH-PHEMT on GaAs	DH-PHEMT on GaAs	LMHEMT and PHEMT on InP
Channel: $In_yGa_{1-y}As$, $y \approx 0.2...0.25$	Channel: $In_yGa_{1-y}As$, $y \approx 0.2...0.25$	Channel: $In_yGa_{1-y}As$, $y \ge 0.53$
$d \approx 30$ nm $d_c \approx 12$ nm	$d \approx 30$ nm $d_c \approx 12$ nm	$d \approx 20$ nm $d_c \le 20$ nm (PHEMT) $d_c \approx 20...80$ nm (LMHEMT)
$\Delta E_c \approx 0.28$ eV	$\Delta E_c \approx 0.28$ eV	$\Delta E_c \ge 0.52$ eV
$\mu_e = 5000...6500\ cm^2/Vs$ $n_s = 1.5...2.5 \times 10^{12} cm^{-2}$ $R_{ch} = 400...600\ \Omega/sq.$	$\mu_e = 5000...6500\ cm^2/Vs$ $n_s = 2.0...3.0 \times 10^{12} cm^{-2}$ $R_{ch} = 300...500\ \Omega/sq.$	$\mu_e = 9500...12000\ cm^2/Vs$ $n_s = 3.0...4.0 \times 10^{12} cm^{-2}$ $R_{ch} = 150...250\ \Omega/sq.$

Advanced Devices: FET Devices
High Electron Mobility Transistor (HEMT)



The energy band diagram for an HFET perpendicular to the source showing the ohmic contact through tunnel junctions.

Advanced Devices: FET Devices
MESFET



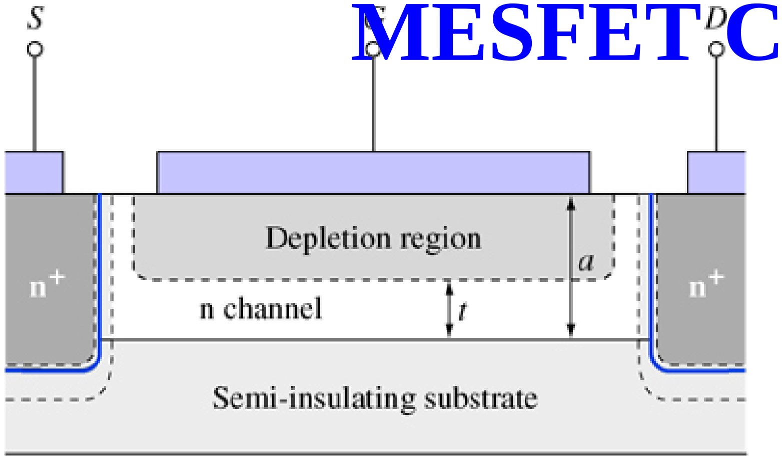
The ability to have semi-insulating material ($\rho \sim 10^6\ \Omega$-cm) in compound semiconductors facilitates the construction of shallow channel (easy to deplete thus fast due to being highly responsive to voltage changes).

Advantages:

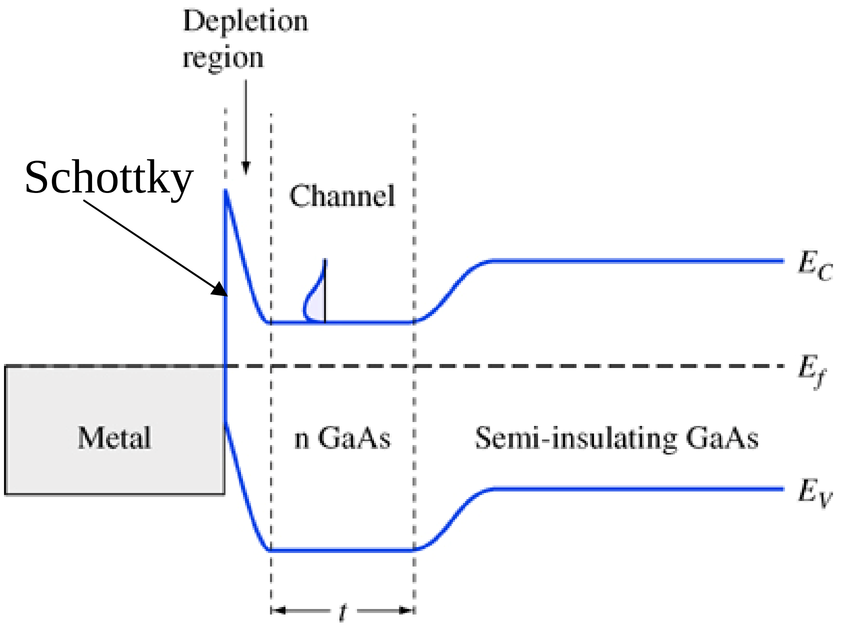
- The mobility is not degraded by surfaces or interfaces like in a MOSFET.
- The device is very fast because the channel thickness can be very precisely controlled (minimized) making the channel easy to deplete with a small gate voltage.
- Cheaper than HEMT since only a thin homojunction epitaxial material is needed on a semi-insulating substrate
- Processing is cheap requiring standard ion implantation and simple metallization

Advanced Devices: FET Devices

MESFET Cross Sectional View



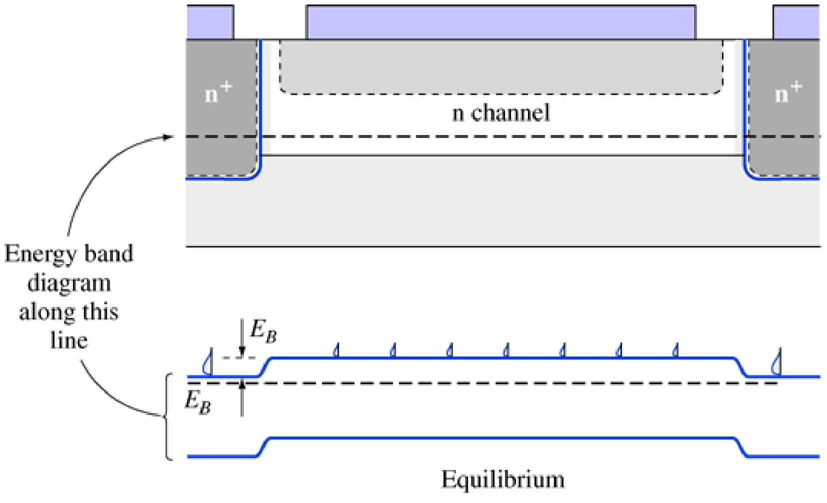
(a)



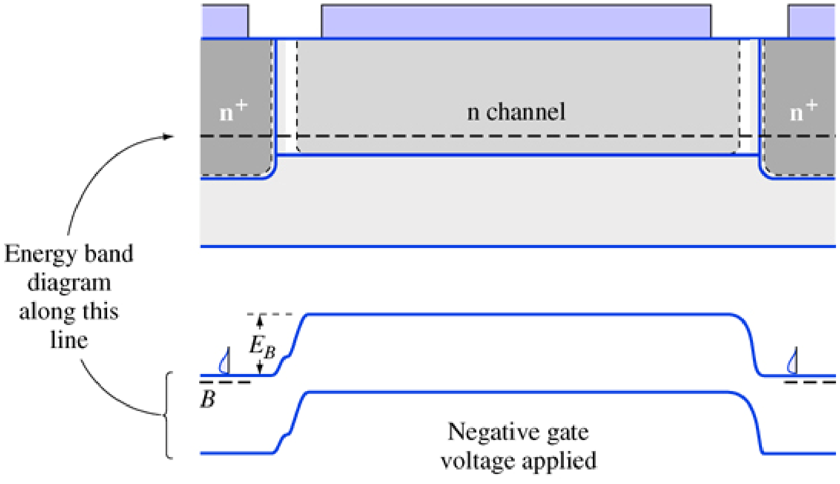
(b)

- **Cross section of a MESFET at equilibrium indicating the depletion regions; (b) the energy band diagram perpendicular to the gate. The channel thickness is *t*.**
- **The Gate is a Schottky barrier, creating the depletion region that thins down the channel.**
- **Adding a reverse bias to the gate will pinch off the channel.**

Advanced Devices: FET Devices
MESFET with no Drain Voltage



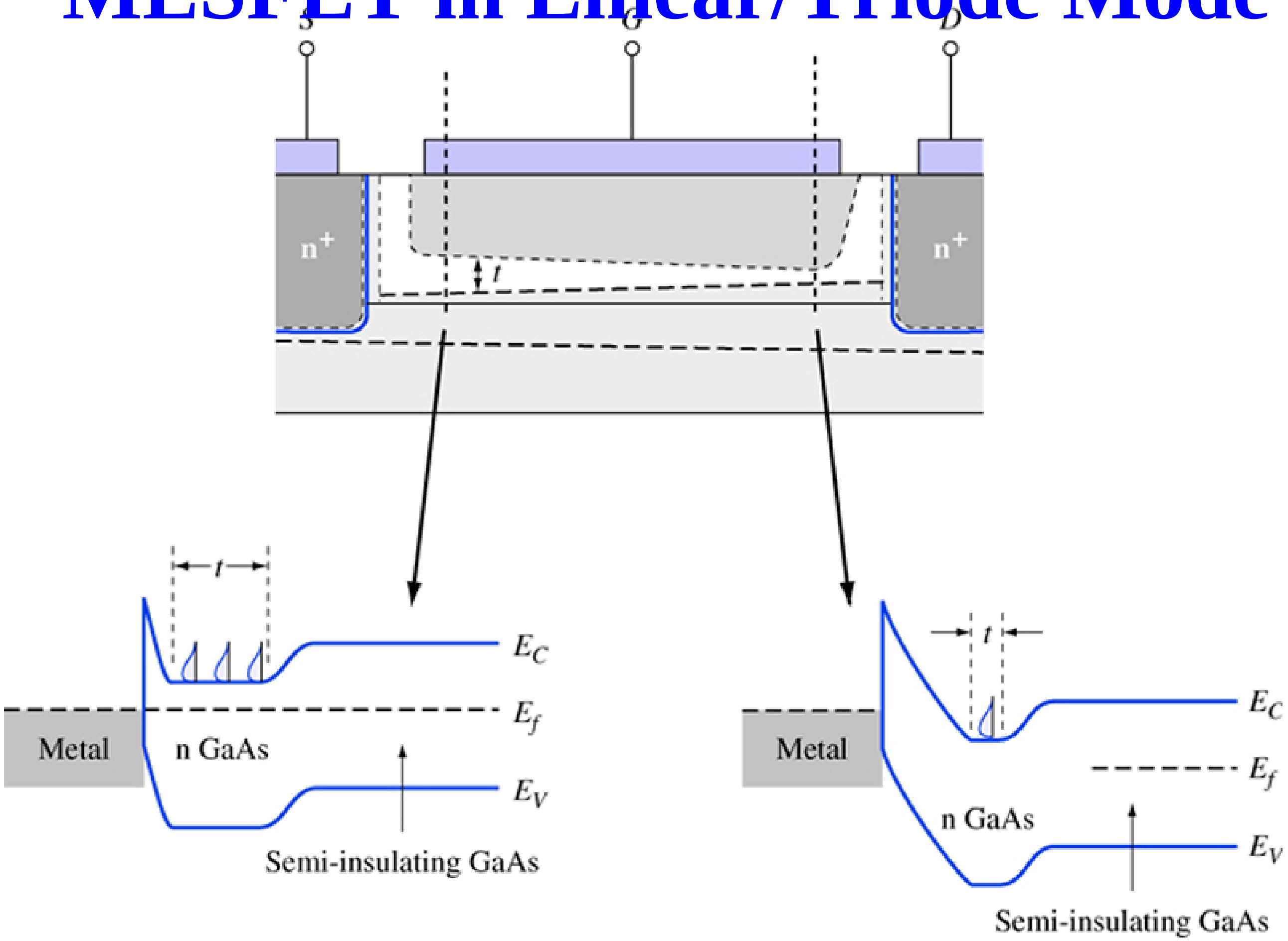
(a)



(b)

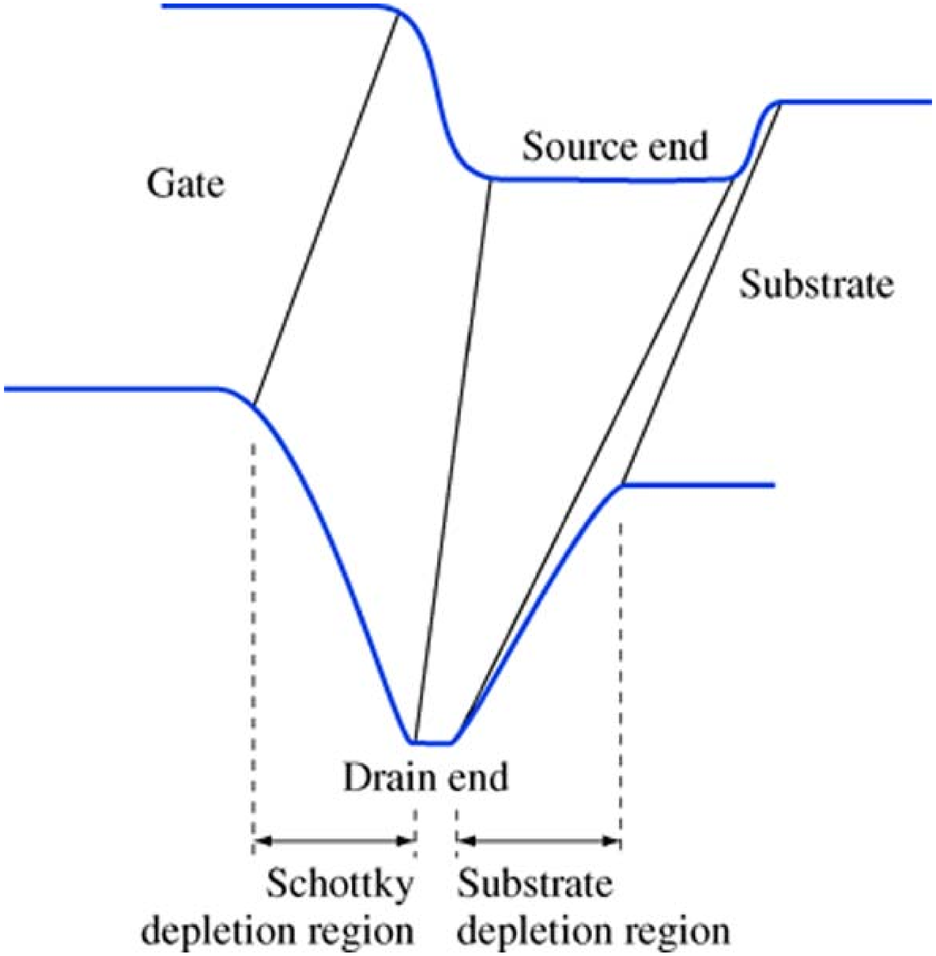
- MESFET energy band diagram and depletion region (a) at equilibrium and (b) for an applied gate voltage that depletes the channel. In the second case, the channel is still n type but it is empty of carriers because of the increased barrier height.

Advanced Devices: FET Devices
MESFET in Linear/Triode Mode



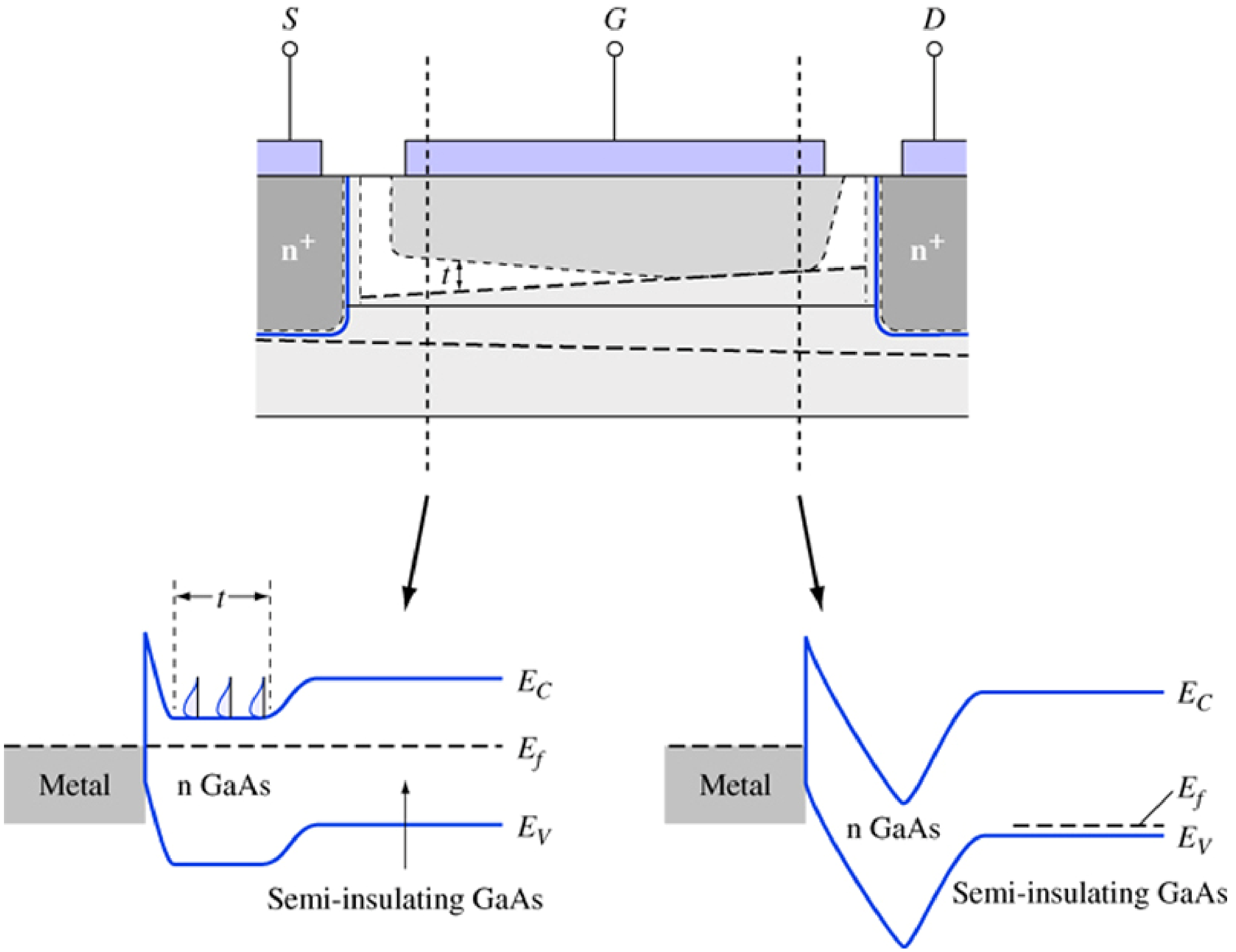
Cross section of a MESFET under small V_{DS} bias and the corresponding energy band diagrams at the source end and drain end of the gate.

Advanced Devices: FET Devices
MESFET 3D Energy Band Diagram



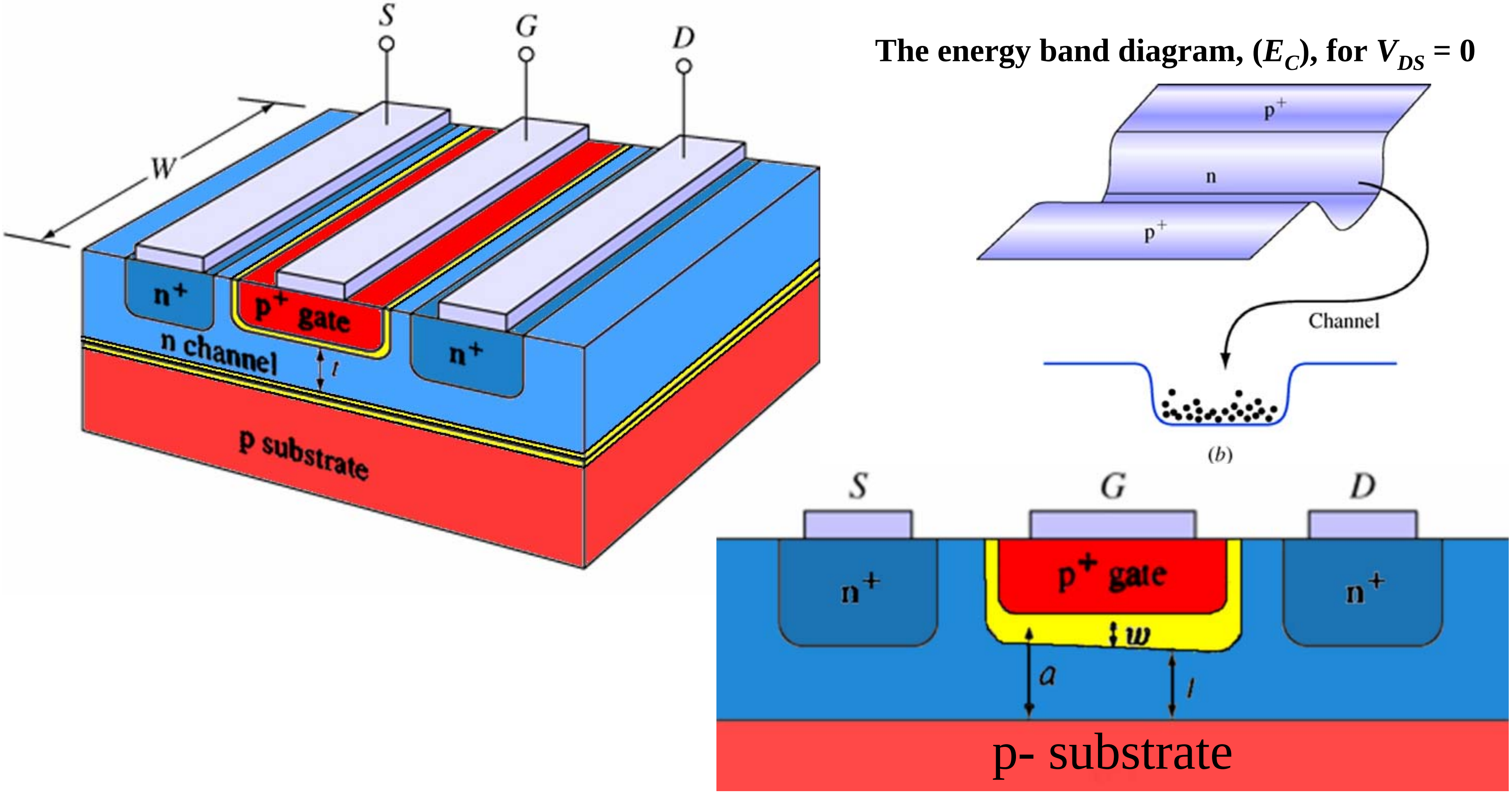
The electron potential energy, (E_C) along the channel of a MESFET for $V_{DS} < V_{DSsat}$. The channel thickness decreases with increasing distance along the channel.

Advanced Devices: FET Devices
MESFET in Pinch off



The same MESFET $V_{DS} > V_{DSsat}$. At the source, the diagram is the same as before. At the drain, however, the two depletion regions overlap pinching off the channel.

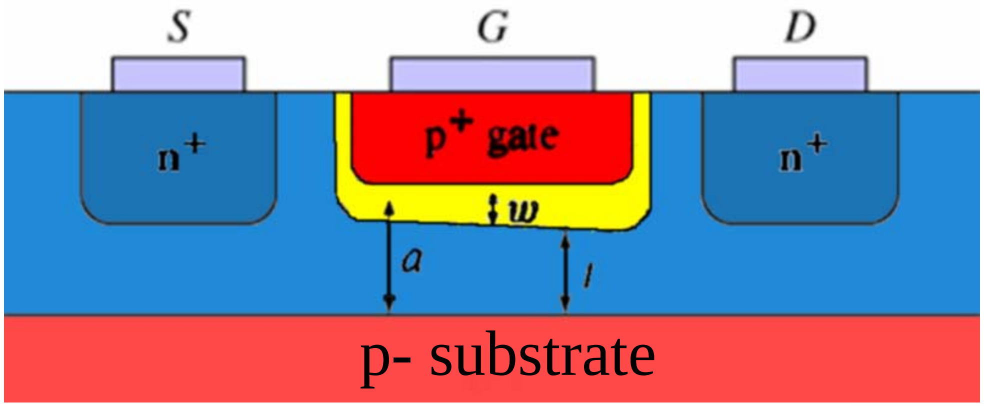
Advanced Devices: FET Devices
Junction FET (JFET)

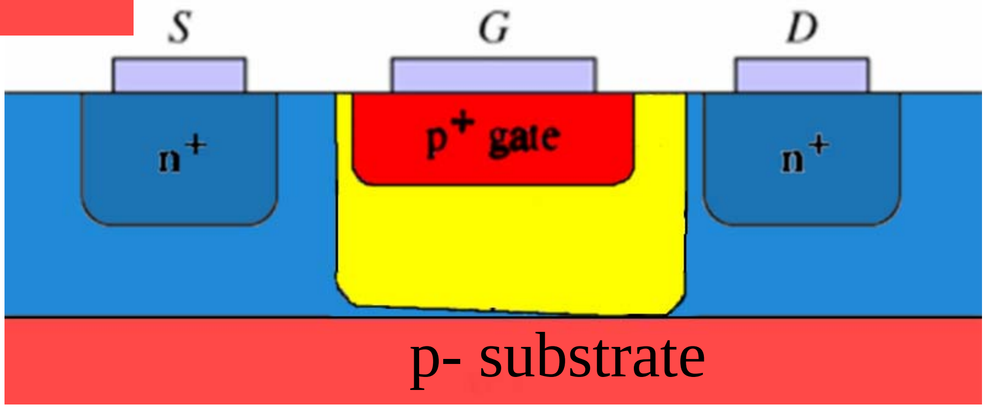


The energy band diagram, (E_C), for $V_{DS} = 0$

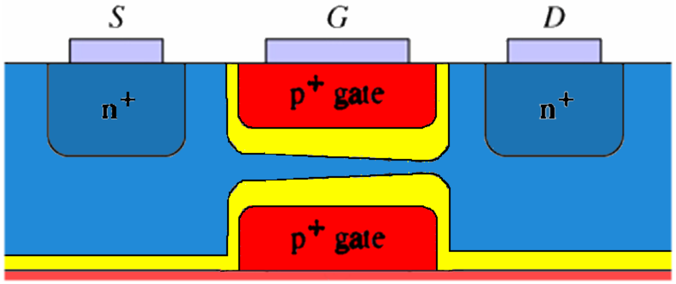
JFET: The yellow shaded areas represent the depletion regions. When $V_{DS} > 0$ (but not yet in saturation) the depletion region at the drain end increases, narrowing the channel and increasing the channel resistance.

Advanced Devices: FET Devices
Junction FET (JFET)

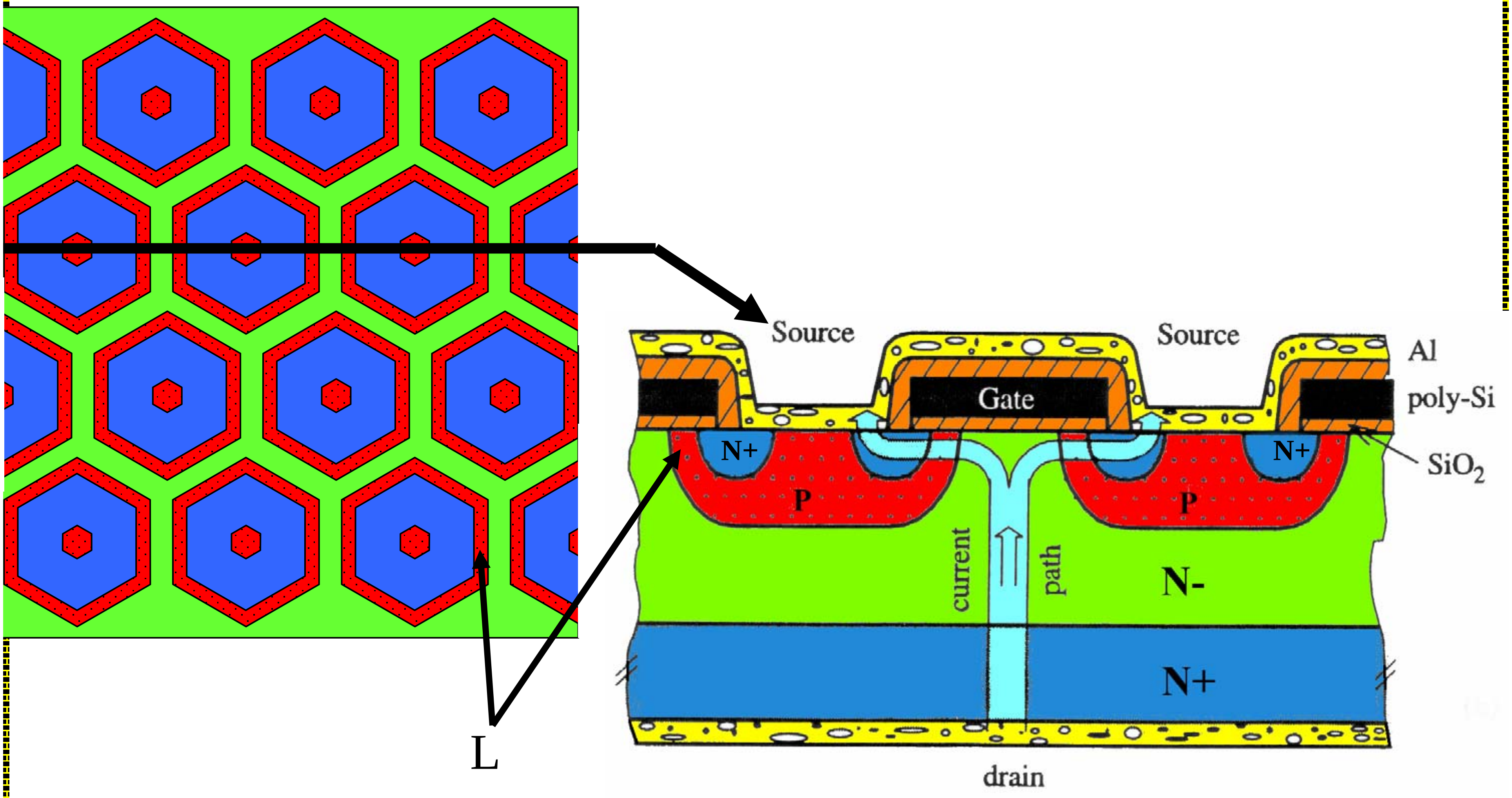




JFET: For higher Gate voltages, the channel can be pinched off. In some JFETs, there is a symmetric gate-channel region even creating a ring and cylindrical channel.

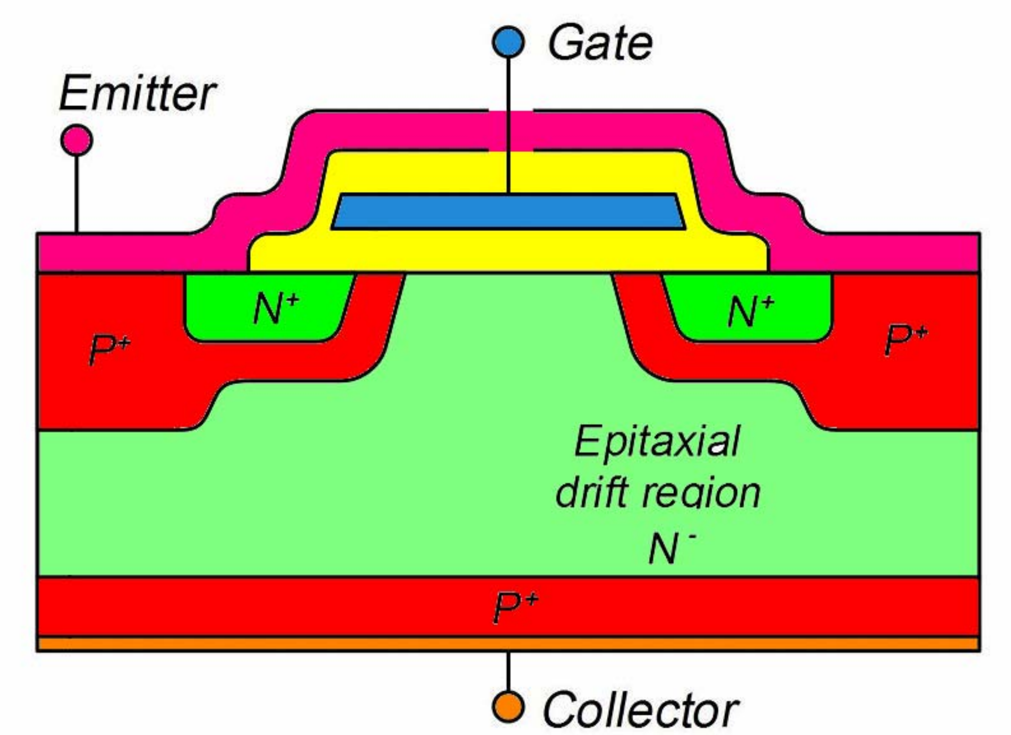


Advanced Devices: FET Devices
Vertical Power MOSFET



Since large electric fields (high voltages) must be supported, thick low doped regions must be used. Thus, most power mosfets use a substantial portion of the substrate as a “drift region” (Green N- region) separate from the “channel region” that controls current flow.

Advanced Devices: FET Devices
Insulated Gate Bipolar Junction Transistor

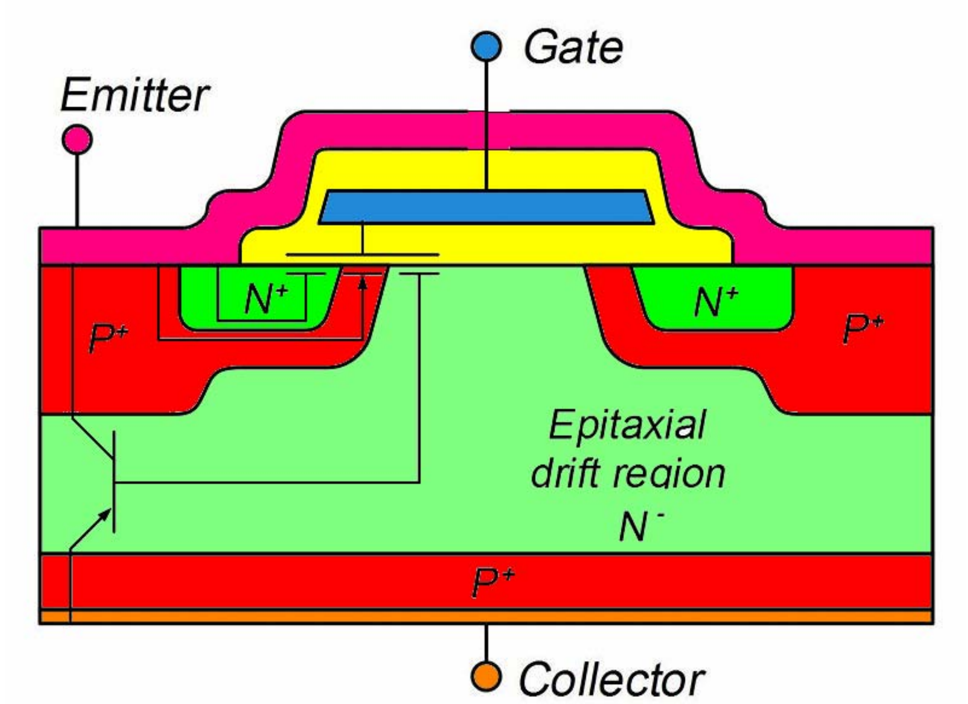


The IGBT is very similar to a n-channel vertical power MOSFET except the n+ drain is replaced with a p+ collector, creating a vertical PNP bipolar junction transistor.

The IGBT is used in primarily applications above 600 V blocking rating whereas power MOSFETs are used below 600V.

IGBTs can handle thousands of volts (off state) with minimal leakage currents and conduct 1000s of amps (on state) with typically a few volts to 10s of volts forward voltage drop (on state).

Advanced Devices: FET Devices
Insulated Gate Bipolar Junction Transistor

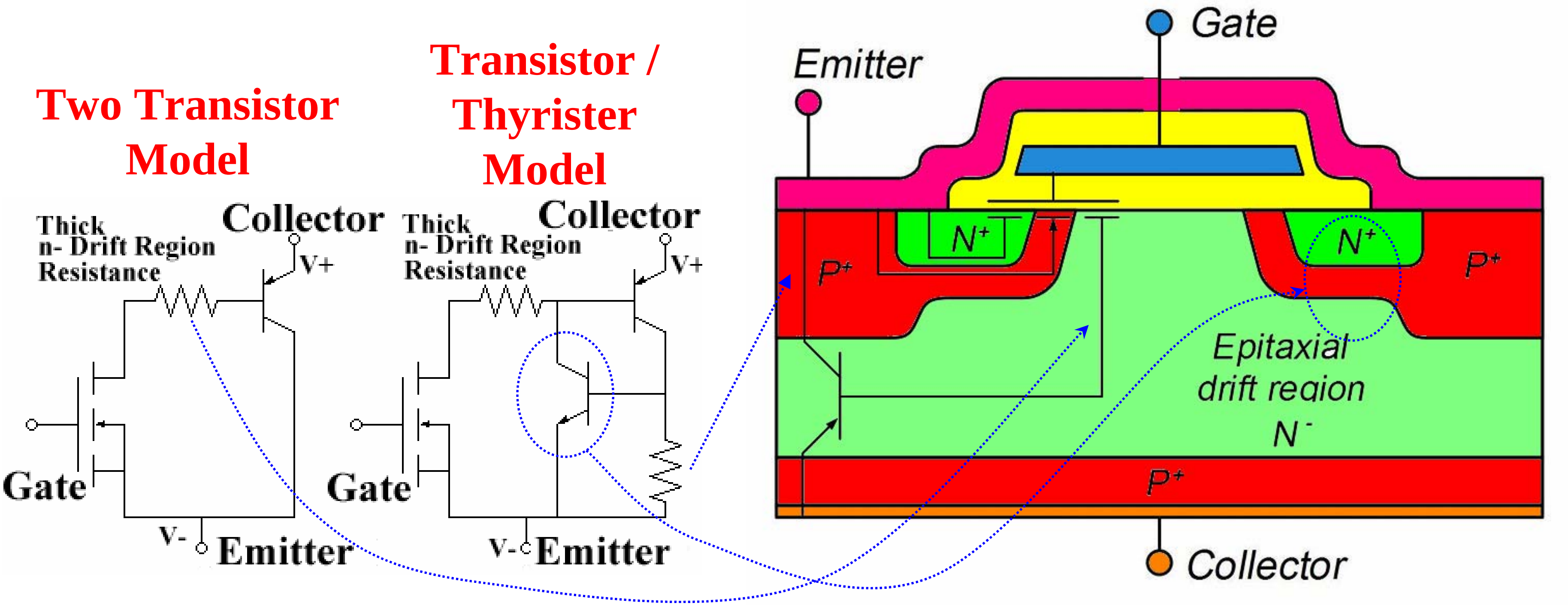


The additional p+ region creates a cascaded connection of a PNP bipolar junction transistor with the surface n-channel MOSFET.

This connection results in a significantly lower forward voltage drop compared to a conventional MOSFET. By injecting minority carriers (holes) from the collector p+ region into the n- drift region during forward conduction, the resistance of the n- drift region is considerably reduced. This minority carrier injection in power devices is called conductivity modulation. When in the off state, this conductivity modulation does not occur allowing the low doped drift region to support very high voltages in the off state.

Since this is a minority carrier device, this results in longer switching time (slower speed) and hence higher switching losses compared to a power MOSFET.

Advanced Devices: FET Devices
Insulated Gate Bipolar Junction Transistor



- •Cathode/Emitter of IGBT=Source of MOSFET=BJT Collector. This connects to negative/smallest voltage.
- •Drain of MOSFET=Base of BJT=Internal Connection to low doped thick drift region.
- •Anode/Collector of IGBT=Emitter of BJT connects to Positive/Largest voltage.
- •Gate turns on Base-Emitter junction turning on emitter –collector current.
- •There is actually a buried npn BJT that forces the IGBT to act like a Thyristor.

Advanced Devices: FET Devices
Flash Memory MOSFET

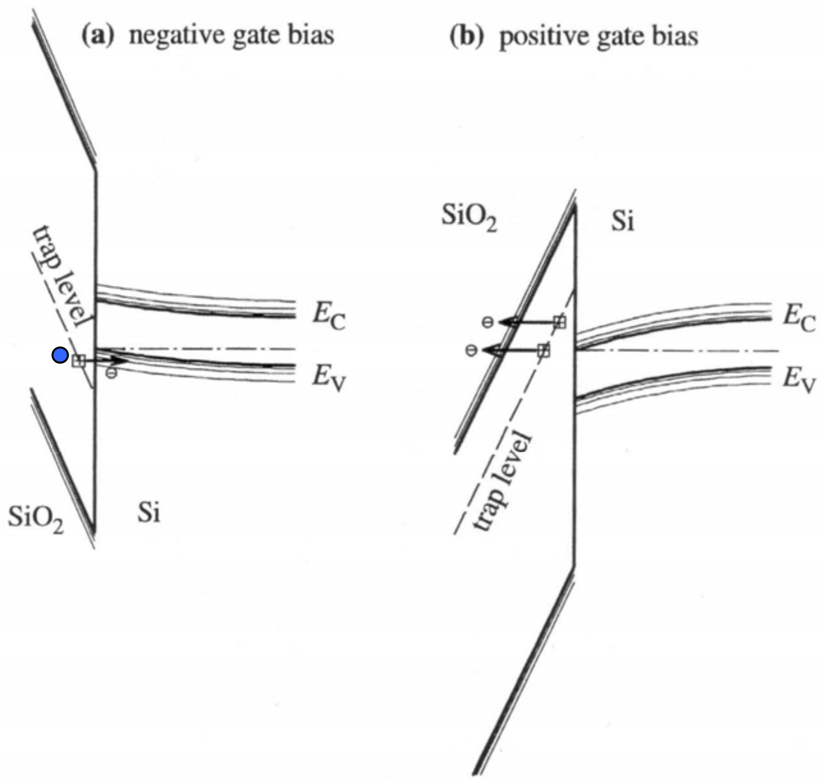


Figure 11.6 Mechanisms of positive gate-oxide charge creation by a high gate-oxide field: (a) negative gate bias and (b) positive gate bias.