Bipolar Junction Transistors (BJTs)
and
Unipolar Transistors (FETs)

(Prepared by Ron, K8DMR, for series of GRARA meetings this year but now only posted on their website because of COVID -19 Pandemic)

including

Junction FETs (JFETs)

Metal-Semiconductor FETs (MESFETs)

and

Metal-Oxide-Semiconductor FETs (MOSFETs)

INTRODUCTION

- A bipolar junction transistor (BJT) is a type of transistor that uses both electrons and holes as charge carriers.
- Current is produced both by electric field action on the carriers (drift current) and by thermal diffusion of carriers from regions of high concentration to regions of lower carrier concentration.
- Which current predominates depends on the region (p or n type material), material thickness, n/p doping, applied electric field, etc.
- BJTs use two p-n type material junctions.

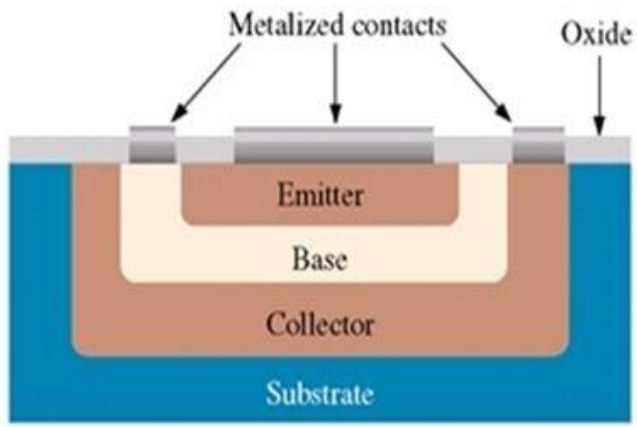
Unipolar transistors such as field effect transistors use only one type of charge carrier, electrons for N-channel FETs and holes for p channel FETs.

FETs either use a single p-n junction (JFET), a single metal-semiconductor junction (MESFET) or no junction at all (MOSFET).

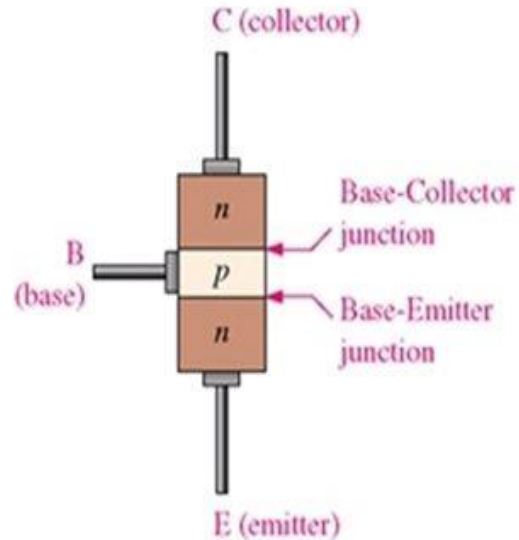
In the MOSFET case the carrier flow is controlled by a metallic plate separated from the semiconductor by an insulation layer, typically SiO2.

Let’s consider the Bipolar Junction Transistor first.

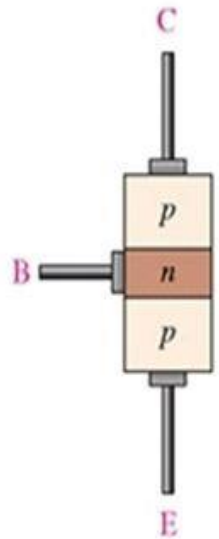
Basic construction of BJT



(a) Basic epitaxial planar structure

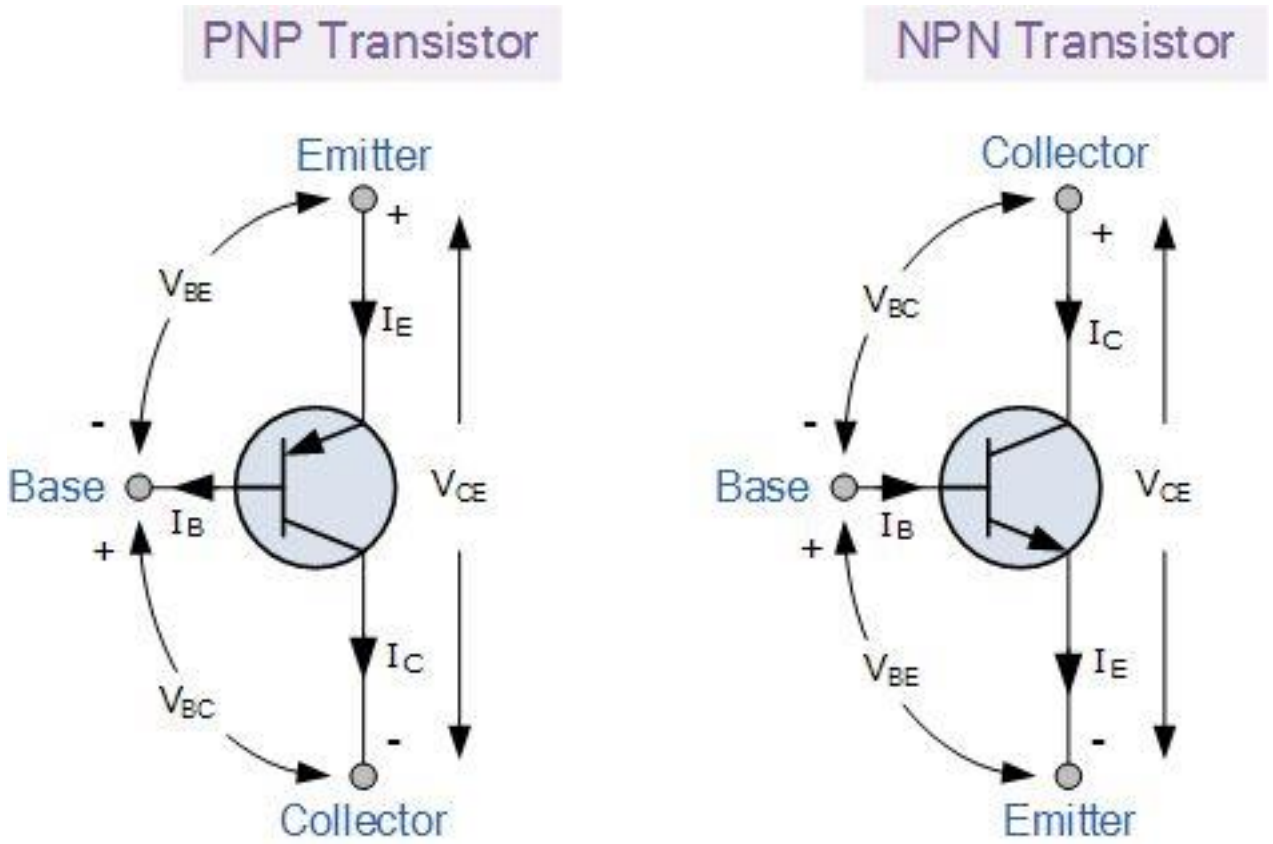


(b) *npn*

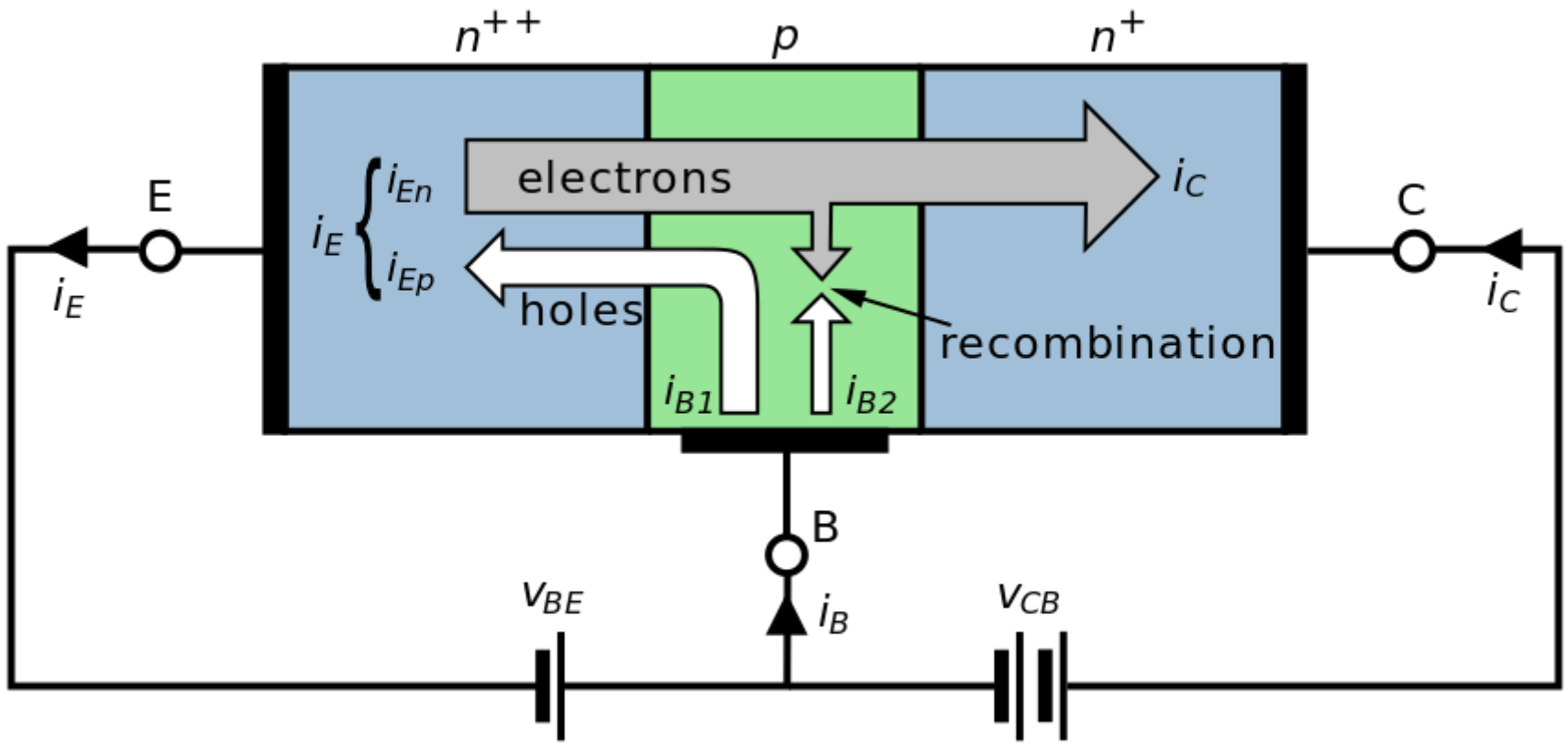


(c) *pnp*

PNP and NPN BJT Circuit Symbols Showing Positive Current Directions and Positive Voltmeter Leads



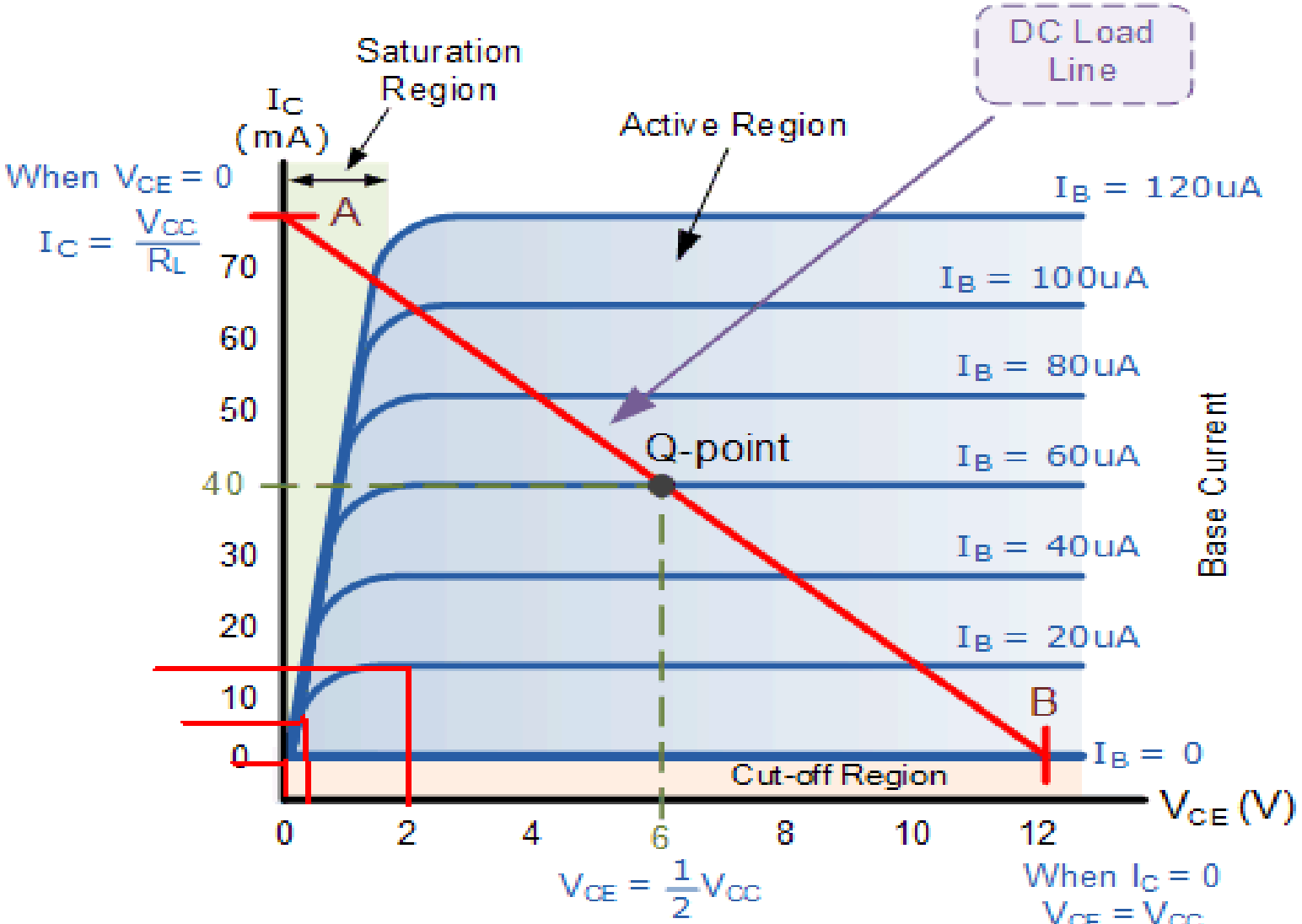
Electron and Hole flow in an NPN BJT in Active Mode



OPERATING REGIONS IN AN NPN BJT

Rc is the assumed collector load resistance

Note that a BJT is a current controlled current source.

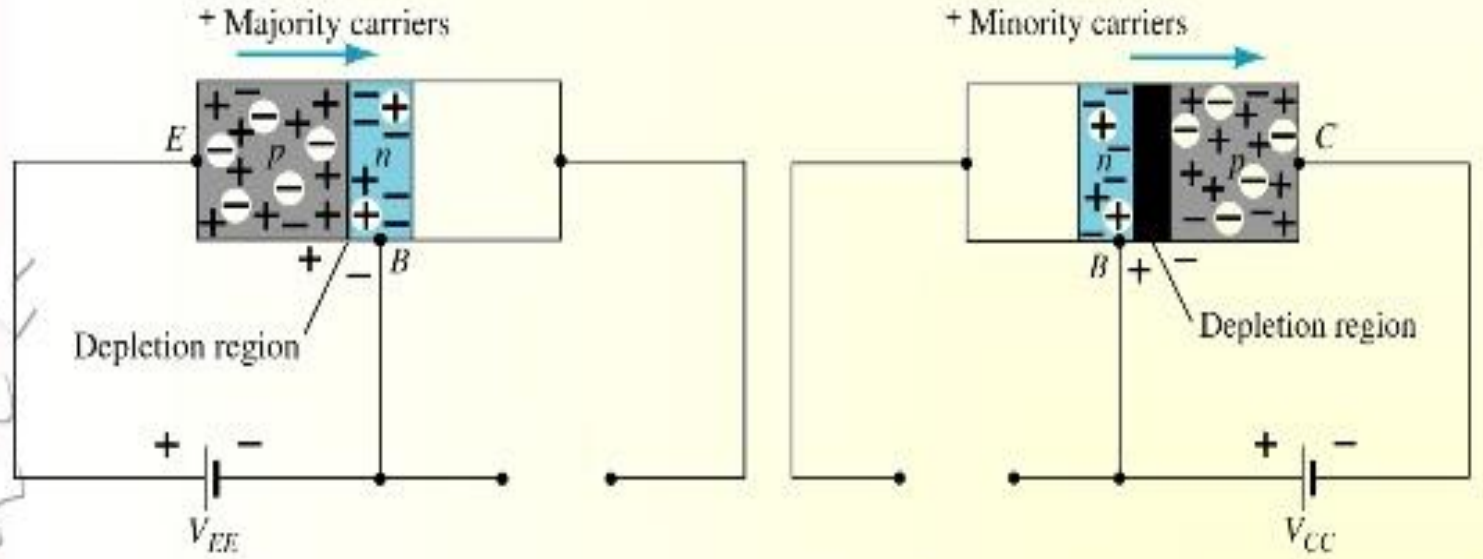


Saturation Mode, Cutoff Mode, Active Mode

- Saturation mode and cutoff mode are the two BJT modes most used in digital circuits.
- In saturation mode both the BE and CB junctions are forward biased. In saturation the CE voltage drop across the transistor is the smallest, ~ 0.2 V.
- Typically, saturation mode corresponds to digital 1 and cutoff mode to digital zero or vice versa.
- Active mode on the other hand is typically used in analog circuits for amplification. One uses a load line to show the bias/operating point.
- These comments hold for both NPN and PNP BJTs.
- We shall treat PNP BJTs briefly next.

PNP Transistor Operation in Active Mode (amplifier)

- One p-n junction of a transistor is reverse-biased, whereas the other is forward-biased.

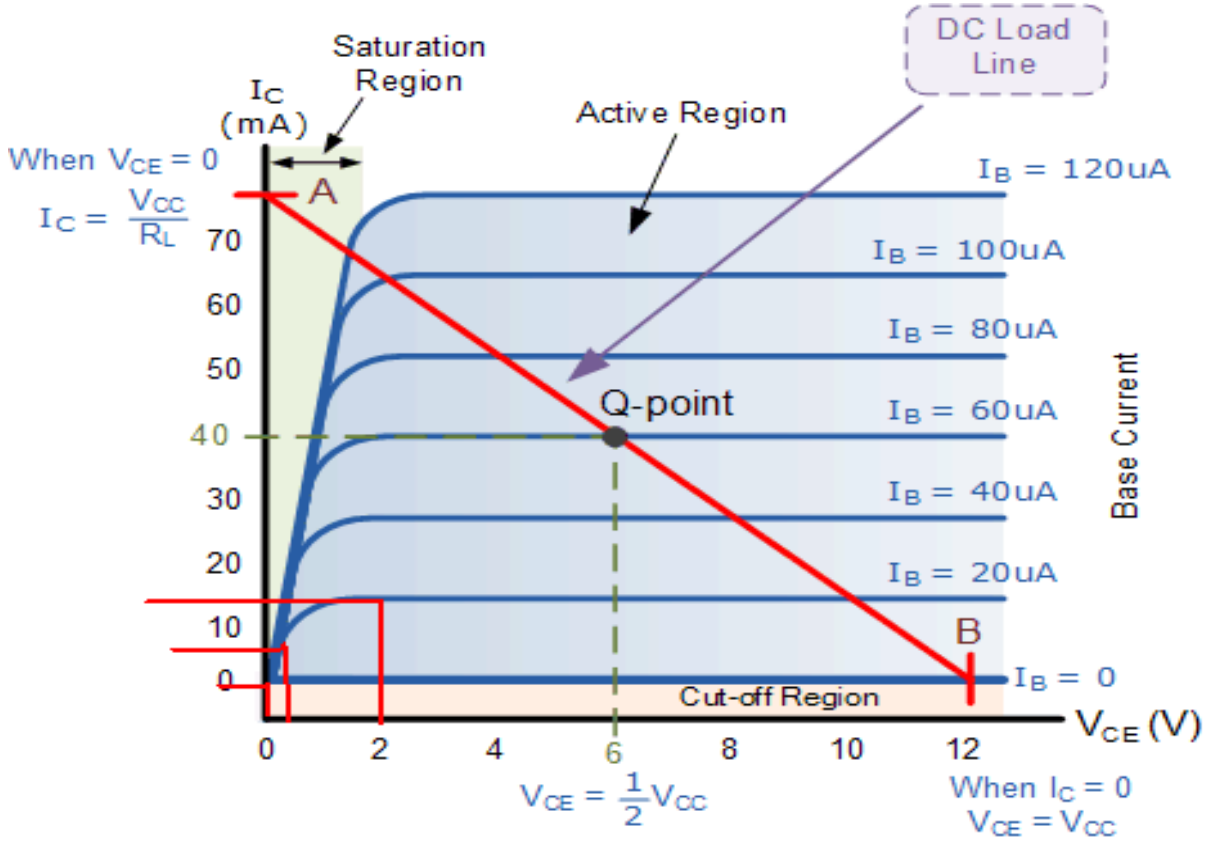


Forward-biased junction of a pnp transistor

Reverse-biased junction of a pnp transistor

PNP Transistor Operating Characteristic (Again assuming collector load resistor Rc present)

- If we just reverse the positive current directions and voltage polarities from those for an NPN transistor then a PNP BJT Characteristic curve will look identical to its equivalent NPN transistor.



FIELD EFFECT TRANSISTORS

- Unlike BJTs which are current controlled current sources, Field Effect Transistors (FETs) are voltage controlled current sources.
- In a FET there are three main elements like in a BJT but they are called the source, gate and drain instead of emitter, base and collector respectively.
- There is 0 gate current in a FET unlike the base current in a BJT which is non-zero.
- There are two main classes of FETs, Junction FETs (J-FETs) and Metal Oxide Semiconductor (MOS-FETs).
- MESFETS (metal semiconductor FETs) are a subclass of JFETs.

JUNCTION FETS and METAL-SEMICONDUCTOR FETS

- Junction FETS have a P semiconductor material to N semiconductor material junction like in diodes and BJTs. Unlike BJTs there is only one such junction in a JFET, between the gate and the channel.
- Current is carried by the majority carriers everywhere in the channel, electrons for an N-channel JFET or MESFET and holes for a P-Channel JFET or MESFET.
- In a MESFET some gate metals form diode-like junctions between the gate and a channel made of single (N or P) material semiconductors. An example is the well-known GaAs FET.
- The action of the gate in a JFET or MESFET is to (downward) modulate the majority carrier current, cutting off the current at a sufficiently negative gate to source voltage for a N-channel JFET or a sufficiently positive gate to source voltage for a P channel JFET.

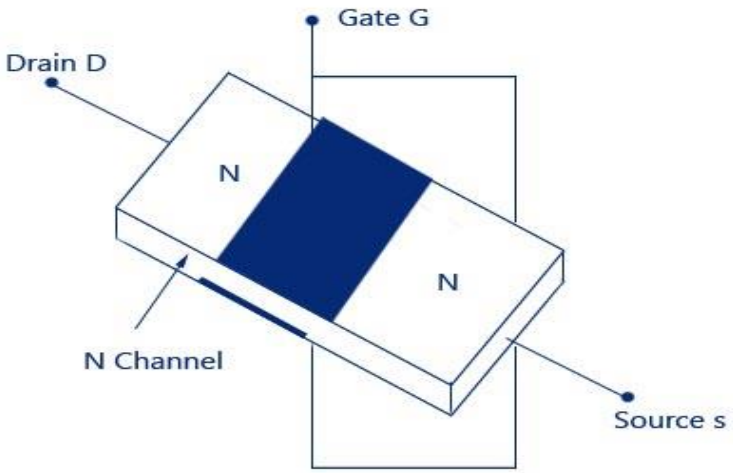
This downward current modulation mode is called the depletion mode.

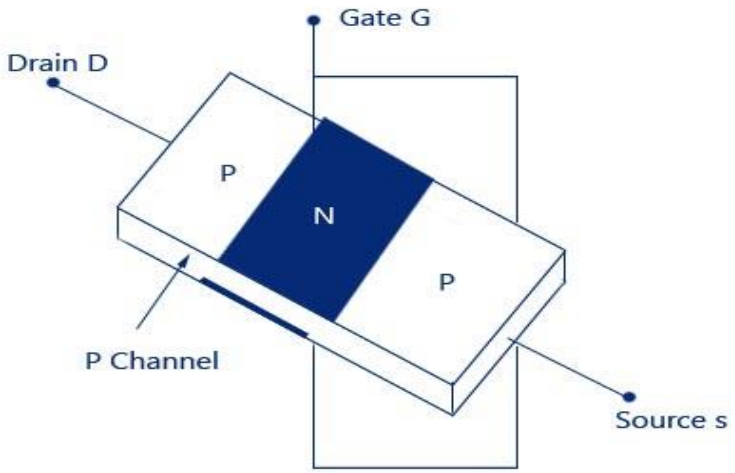
JFETs and their MESFET cousins are always operated in depletion mode.

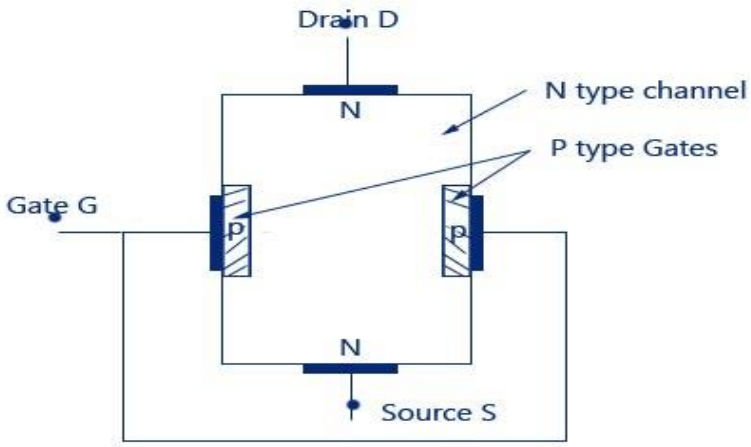
JFET/MESFET current between source and drain is always maximum at 0 gate to source voltage.

In a JFET (or MESFET) if the gate ever became forward biased w.r.t. the source, a non-zero current would flow through the diode junction and the device could burn out.

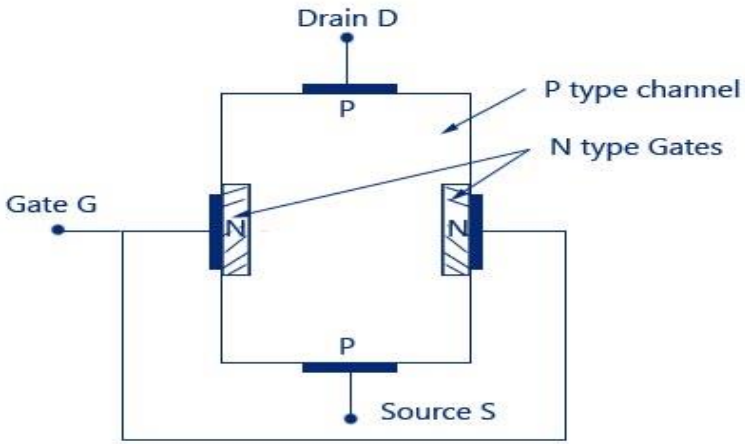
TYPICAL JFET CONSTRUCTION







N Channel JFET



P Channel JFET

JFET Junction Field Effect Transistors

JFET/MESFET SYMBOL DIAGRAMS

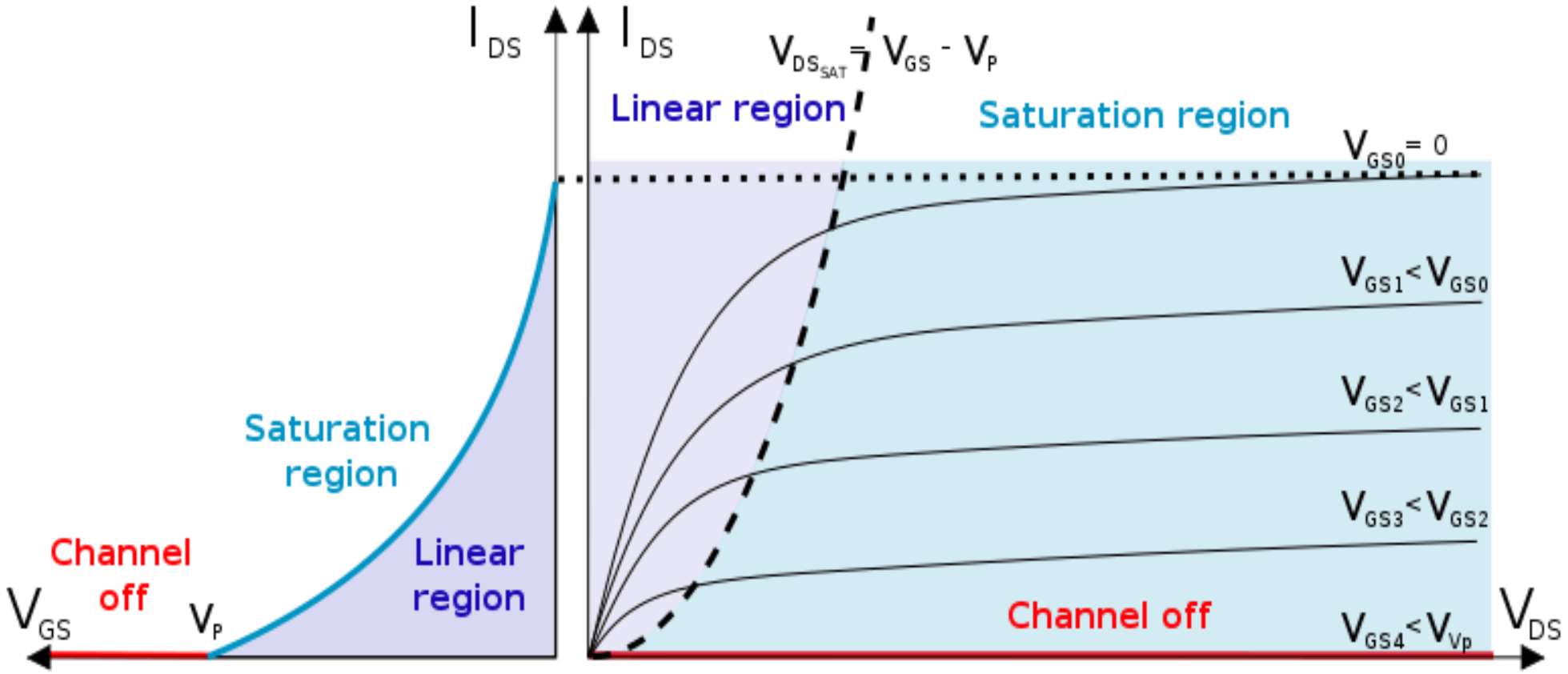
Positive gate current, if it were allowed, would be in the direction of the arrows below.

N-Channel JFET *P-Channel JFET*

Schematic Symbols For JFETs

N CHANNEL JFET OPERATING CHARACTERISTIC

(Vp, the pinchoff voltage, is a negative value)



At 0 gate to source voltage max current flows. The source to drain path looks like a low value resistor.

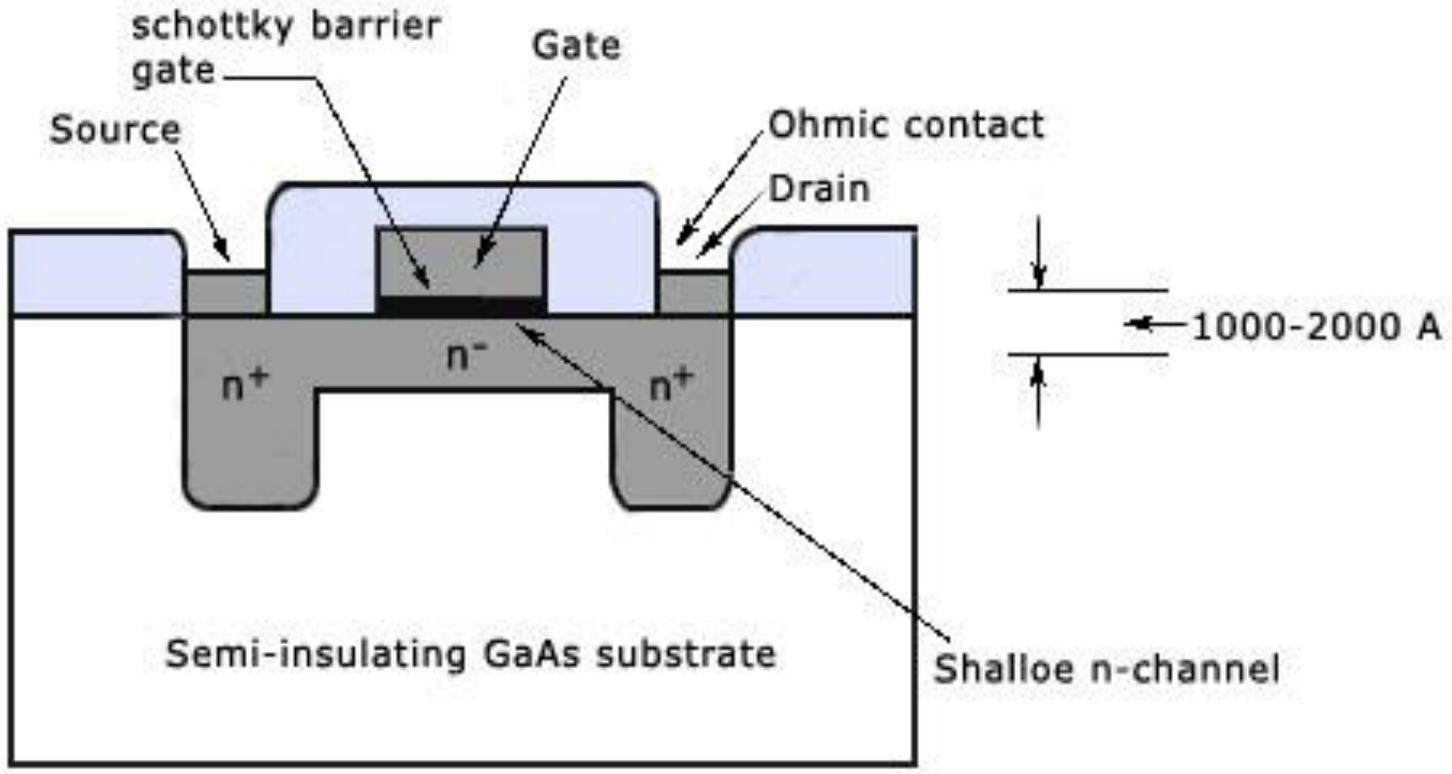
As the gate voltage is reduced below 0 (goes negative) the source to drain current path becomes constricted and less current can flow.

At the pinch-off voltage (-4 volts, say) the effective source to drain resistance becomes infinite and current flow ceases.

For a P-Channel JFET simply reverse the positive directions/polarities of the currents/voltages and the same characteristic pertains.

An Additional Word on MESFETS

These do not use P/N junctions but the metal semiconductor interface still behaves like a diode and can be reverse biased to operate in depletion mode as in a JFET.



The MESFET is used in many RF amplifier applications. where its characteristics give it an edge over other technologies.

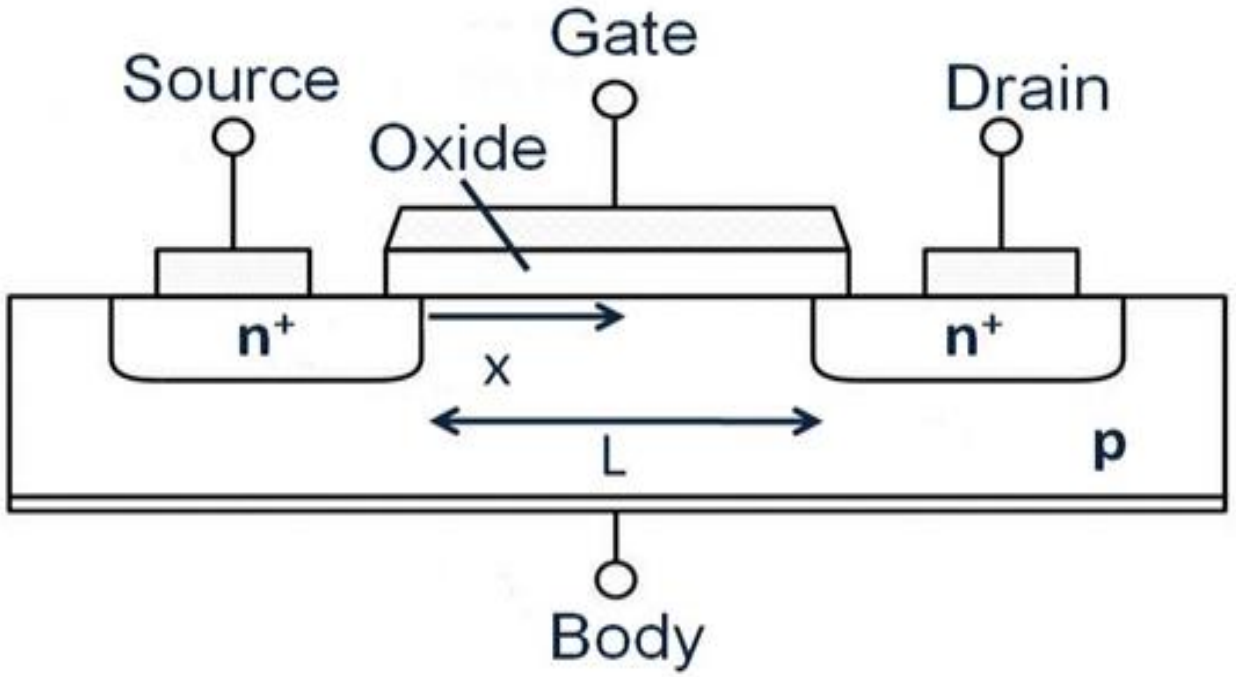
Key characteristics of a GaAs MESFET include:

- ***High electron mobility:*** The use of Gallium Arsenide or other high performance semiconductor materials provides for a high level of electron mobility which is required for high performance RF applications. MESFET semiconductor technology has enabled amplifiers using these devices that can operate up to 50 GHz and more, and some to frequencies of 100 GHz.
- ***Low capacitance levels:*** The Schottky diode gate structure results in very low stray capacitance levels which lend themselves to excellent RF and microwave performance.

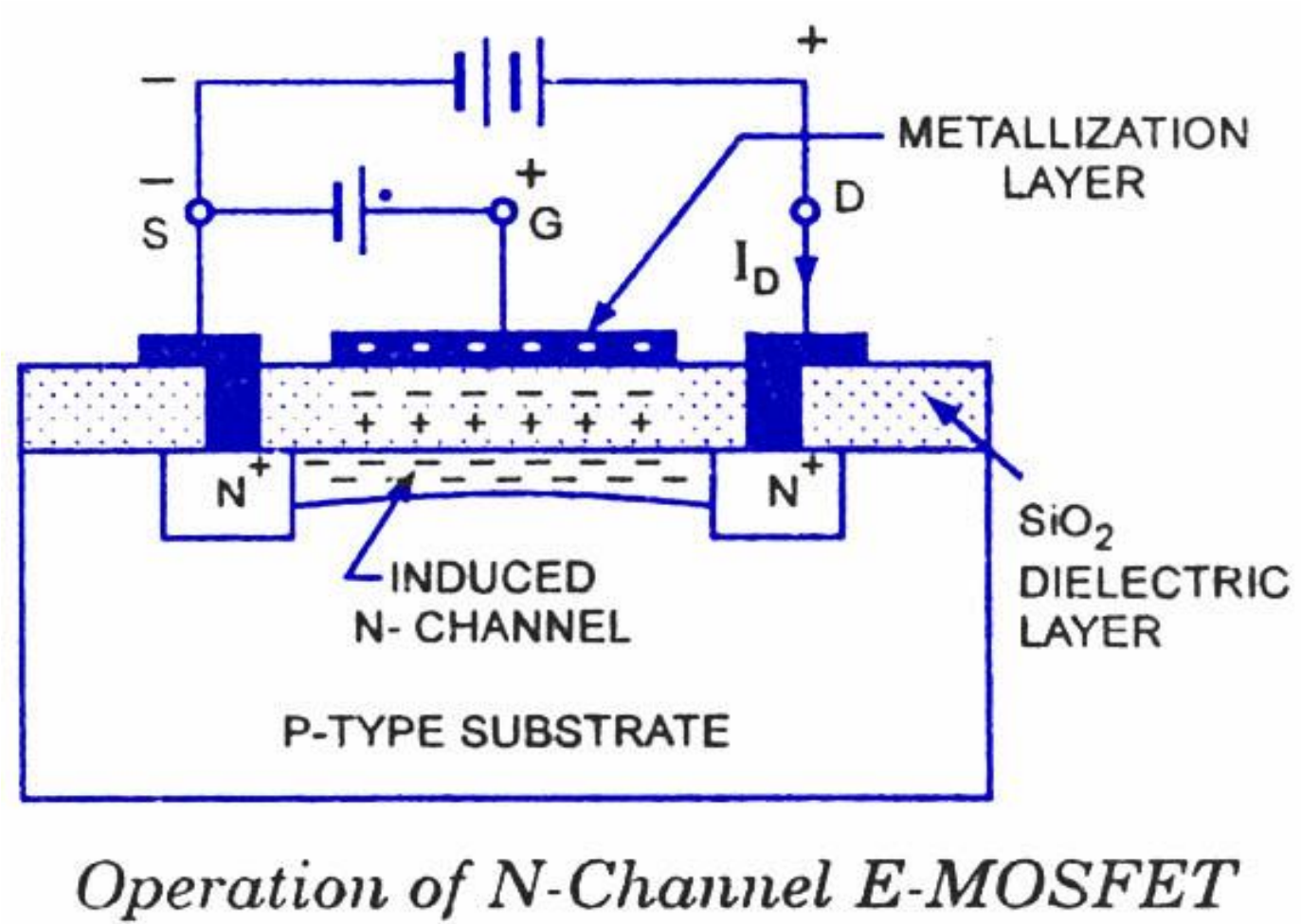
High input impedance: The MESFET has a very much higher input when compared to bipolar transistors as a result of the non-conducting diode junction.

Finally let's move on to MOSFETS.

- Unlike JFETs which only operate in depletion mode both depletion mode (d-MOSFET) and enhancement mode(e-MOSFET) MOSFETs exist.
- We shall look at enhancement mode MOSFETs first.
- Consider an N-channel e-MOSFET. Construction is shown below..



Normal Operation of an N-channel e-MOSFET



Operation of N-Channel E-MOSFET

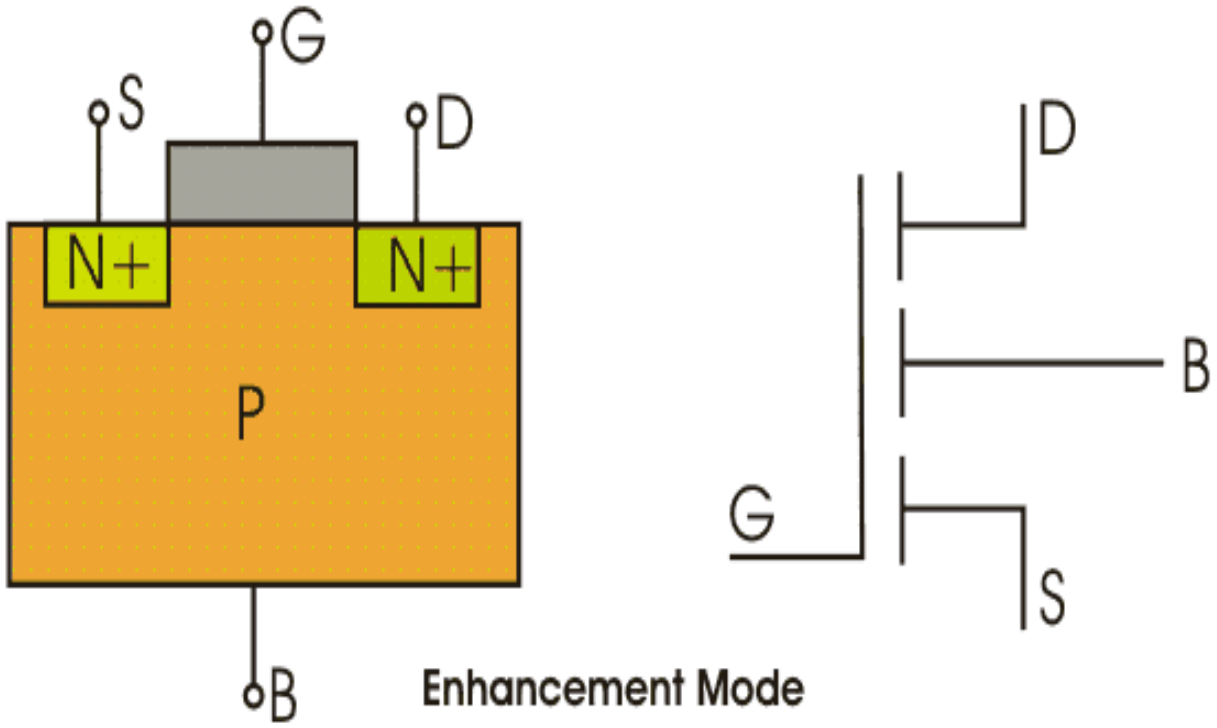
Unlike a JFET, in an e-MOSFET conduction is by minority carriers, here electrons in the p material slab/substrate.

With 0 V on the gate there is no path for the available conduction electrons to get from the n+ source to the n+ drain, no matter how high the drain voltage is with respect to the source.

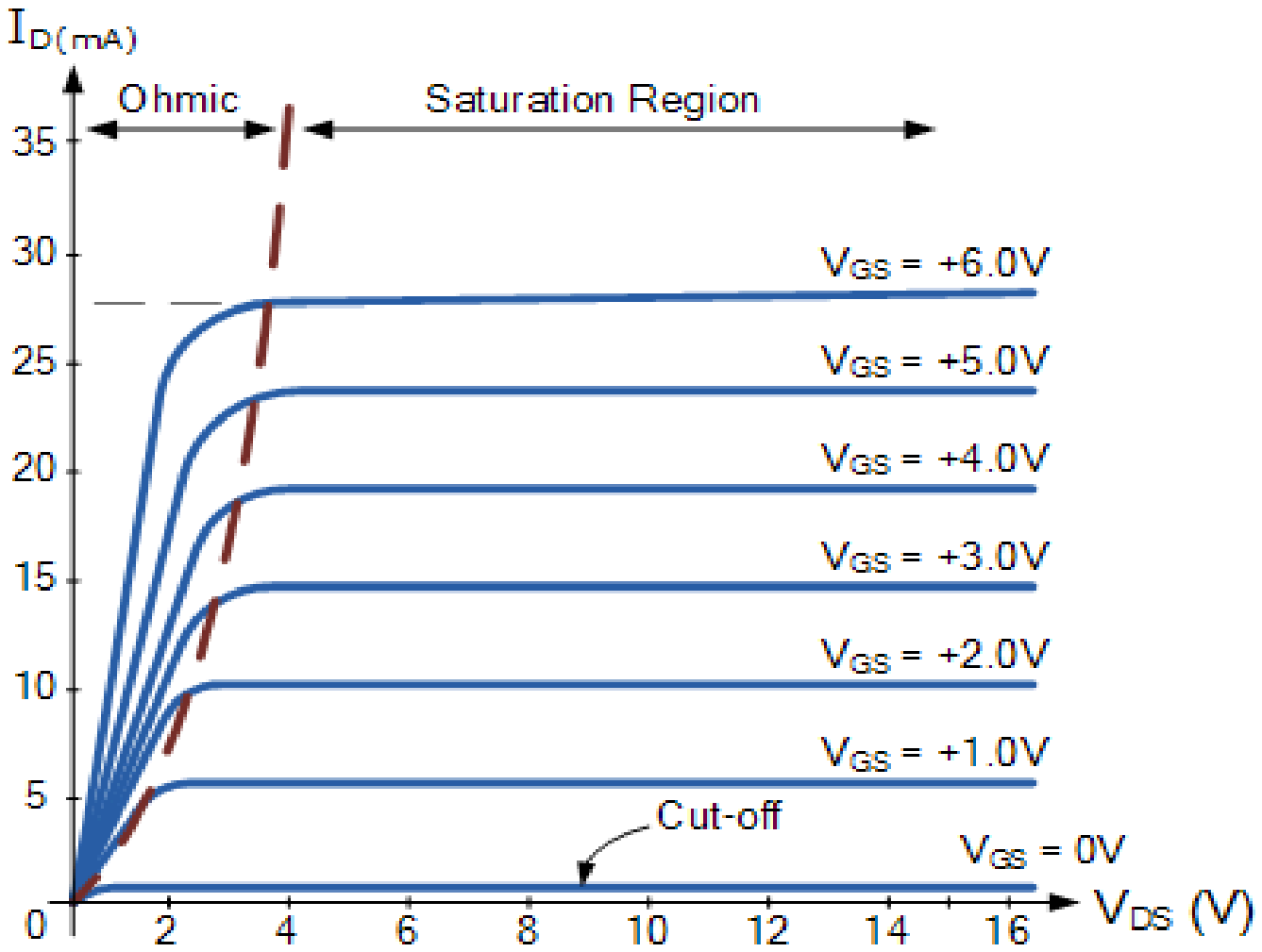
However, with a positive gate voltage minority carriers (electrons) from the small number of N donors still present in the P body get attracted to lie just under the oxide. This forms an N channel and electron conduction can take place between source and drain. This amounts to a positive current from drain to source.

Below is the electronic symbol for an N-channel e-MOSFET

Note the Source to Drain path is shown dashed, indicating no current flows at 0 gate-to-source voltage.



Below is a typical operating curve for an N-Channel MOSFET operating in enhancement mode.



Finally, MOSFETS may also be operated in depletion mode.

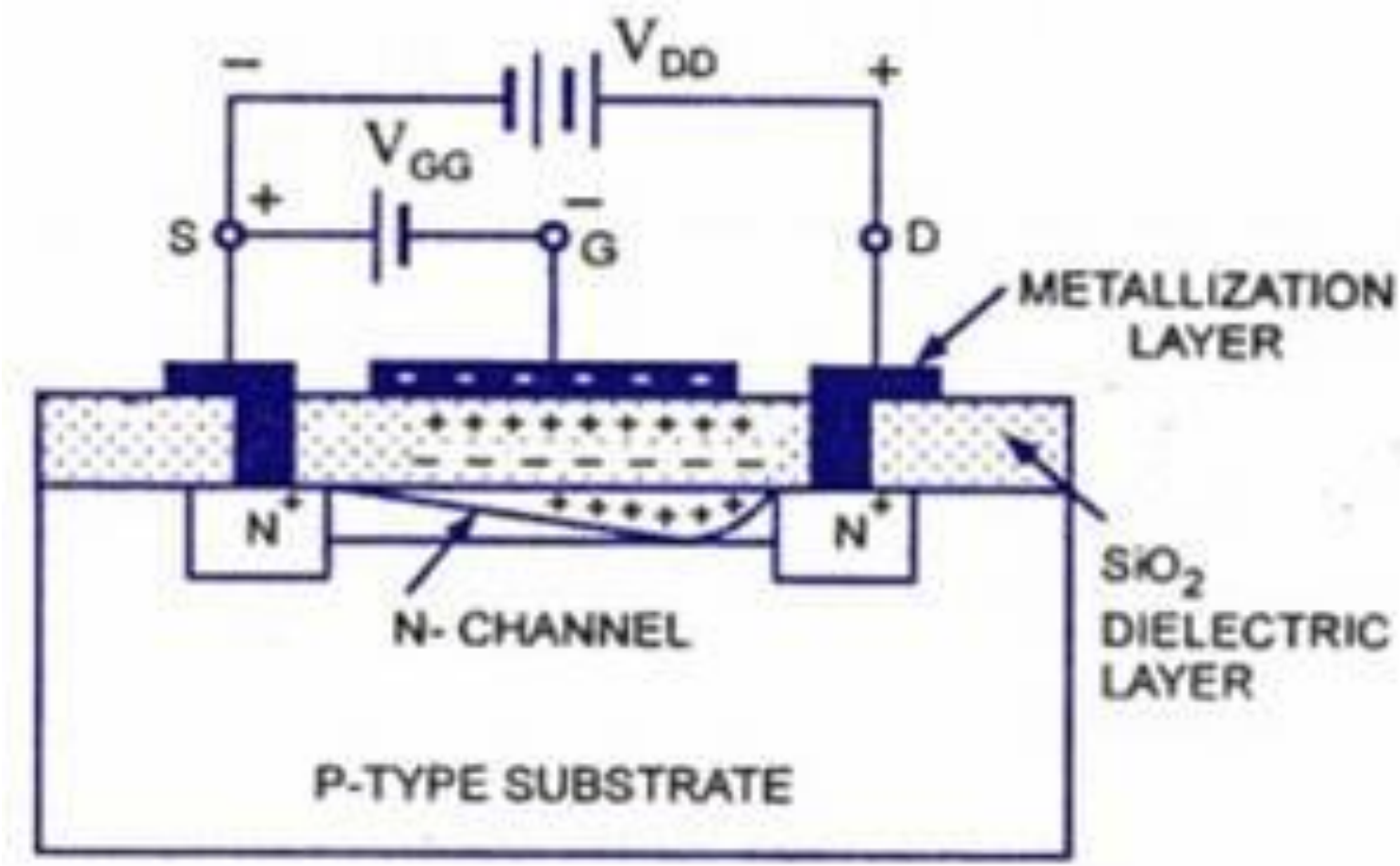
Like JFETs a d-MOSFET is on (conducting) with 0 gate to source voltage and normal drain voltage.

Conduction in depletion mode is then by majority carriers in the semiconductor channel (electrons in an N-channel FET and holes in a P-channel FET) similar to a JFET.

At a sufficiently negative gate-to-source voltage assuming an n-channel d-MOSFET the channel is pinched off.

Of course if the gate-to-source voltage swings positive there still is no bias gate current due to the oxide layer. The MOSFET then is operating in enhancement mode.

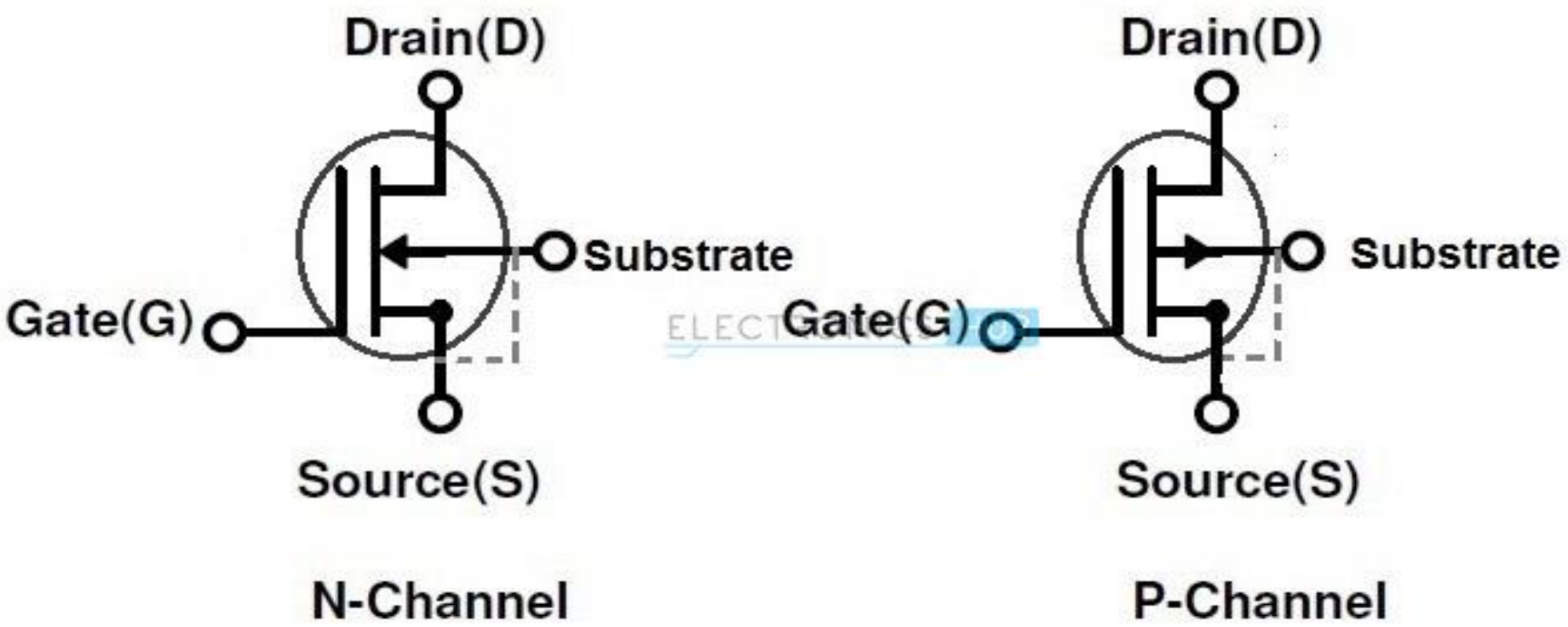
Depletion Mode Operation of an N-channel MOSFET



Depletion Mode Operation

D-MOSFET Concluded

- Below are the typical circuit symbols for denoting d-MOSFETs.
- Note the substrate now is the opposite material from the channel.



U-Tube Video Reference by Alan, W2AEW

- Back to Basics #219 JFETs and MOSFETs
  - https://www.youtube.com/watch?v=oambDFa0Pr8