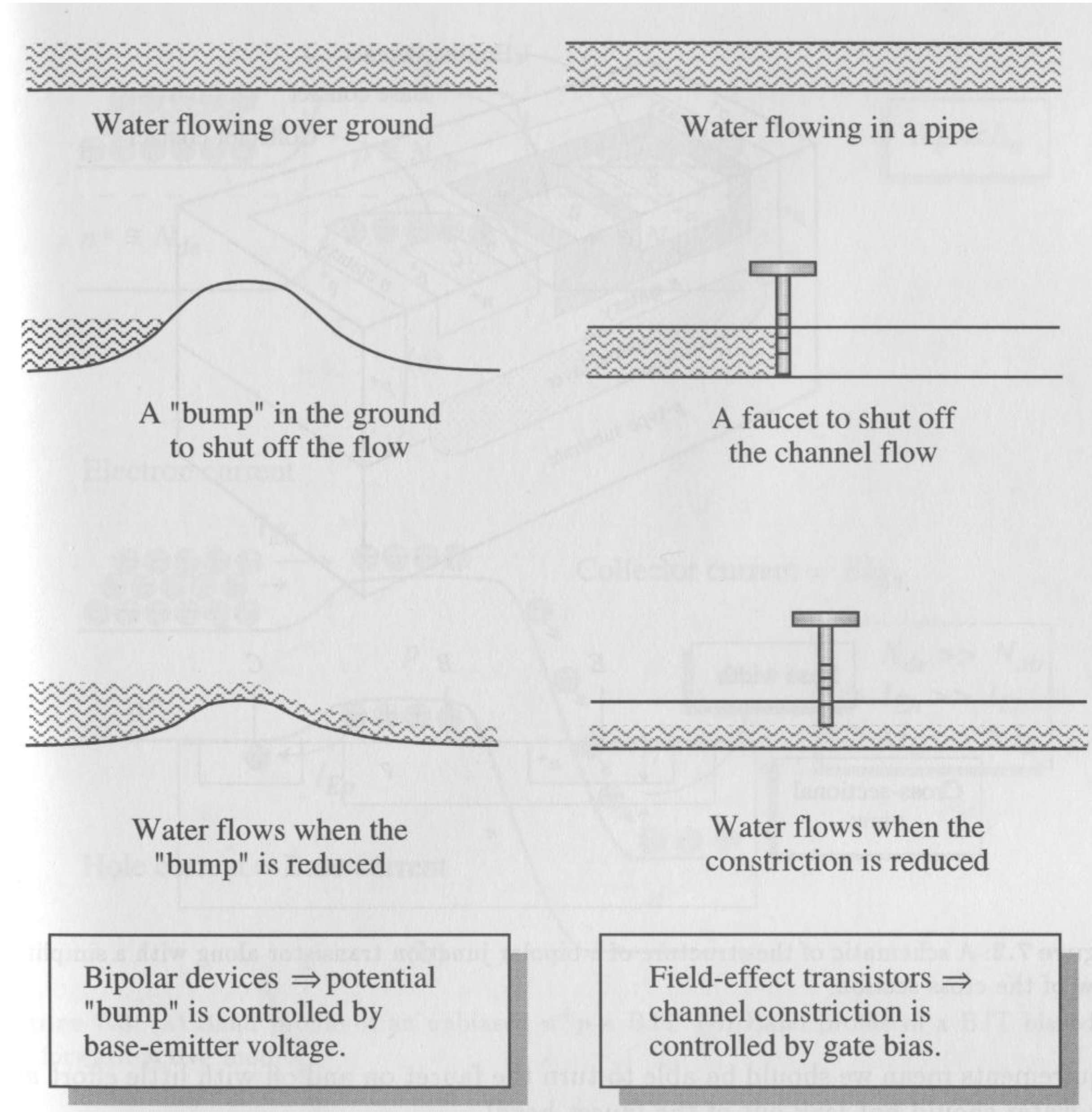
Lecture 9: Transistors

- The Bipolar transistor – definitions
  - Modes of operation
- Schottky transistors
- JFET
- MESFET
- MOSFET

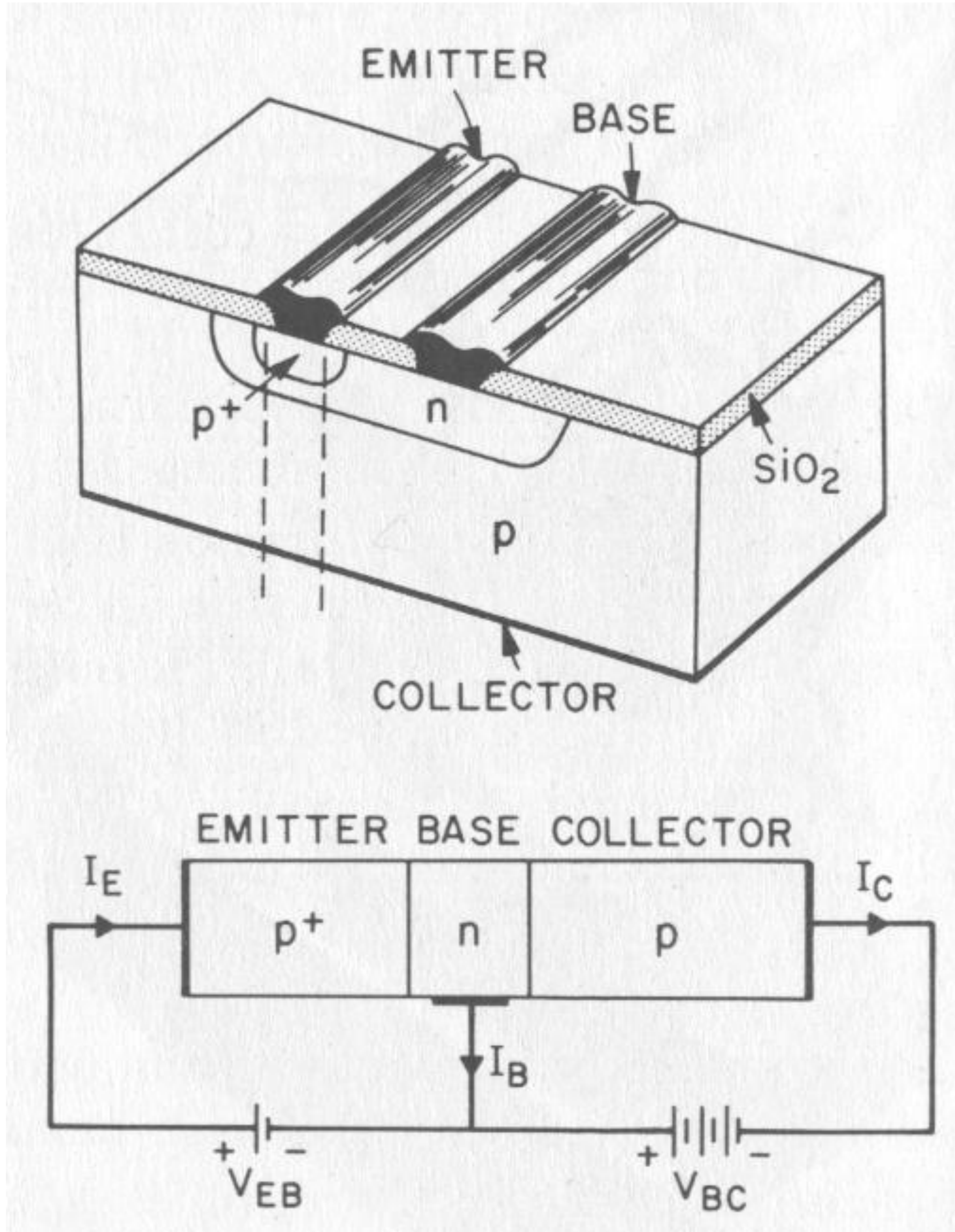
Bipolar Transistor

- The bipolar transistor:
  - Was invented in 1948 by John Bardeen and Walter Brittain.
  - Its principle of operation was explained by W. Shockley a year later.
- A transistor is a three terminal device with the goal of using a small input to control a large output.
- The input could be an incoming weak signal to be amplified, or a digital signal.
- The Bipolar Junction Transistor (BJT) essentially consists of a back-to-back p-n diode.
- The device could have doping of the form *n-p-n* or *p-n-p*.
- For a *n-p-n*, the *p* region forms the **base**, the lower *n*-region is the **collector** and the heavily doped *n* region is called the **emitter**.

Principles of the Bipolar Transistor

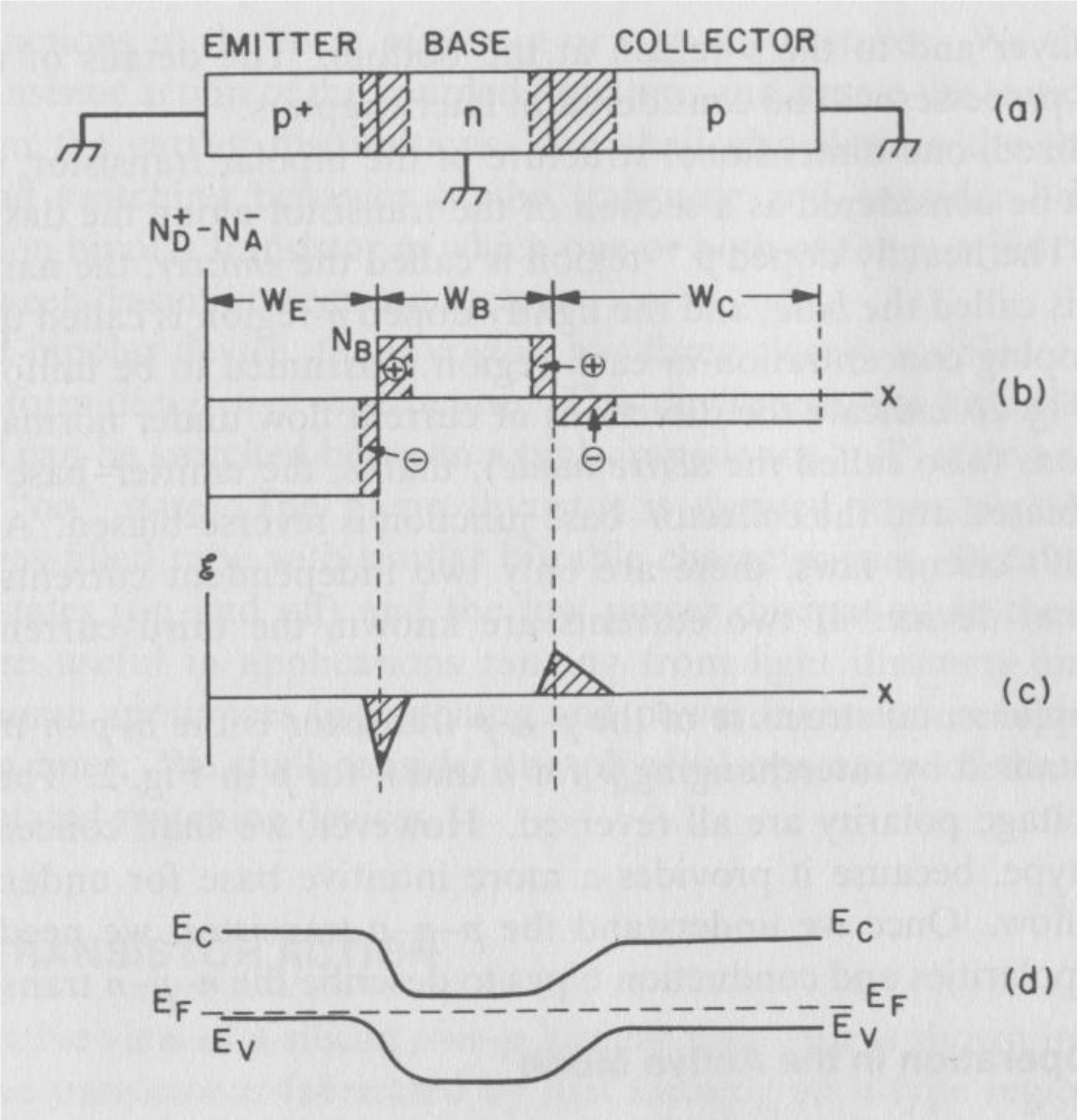


Bipolar transistor schematic



p-n-p transistor at equilibrium

- For a *p-n-p* transistor the energy band profile is a simple extension of the *p-n* junction.
- At thermal equilibrium (all 3 connectors grounded) there is no net current flow, hence the Fermi level is a constant.

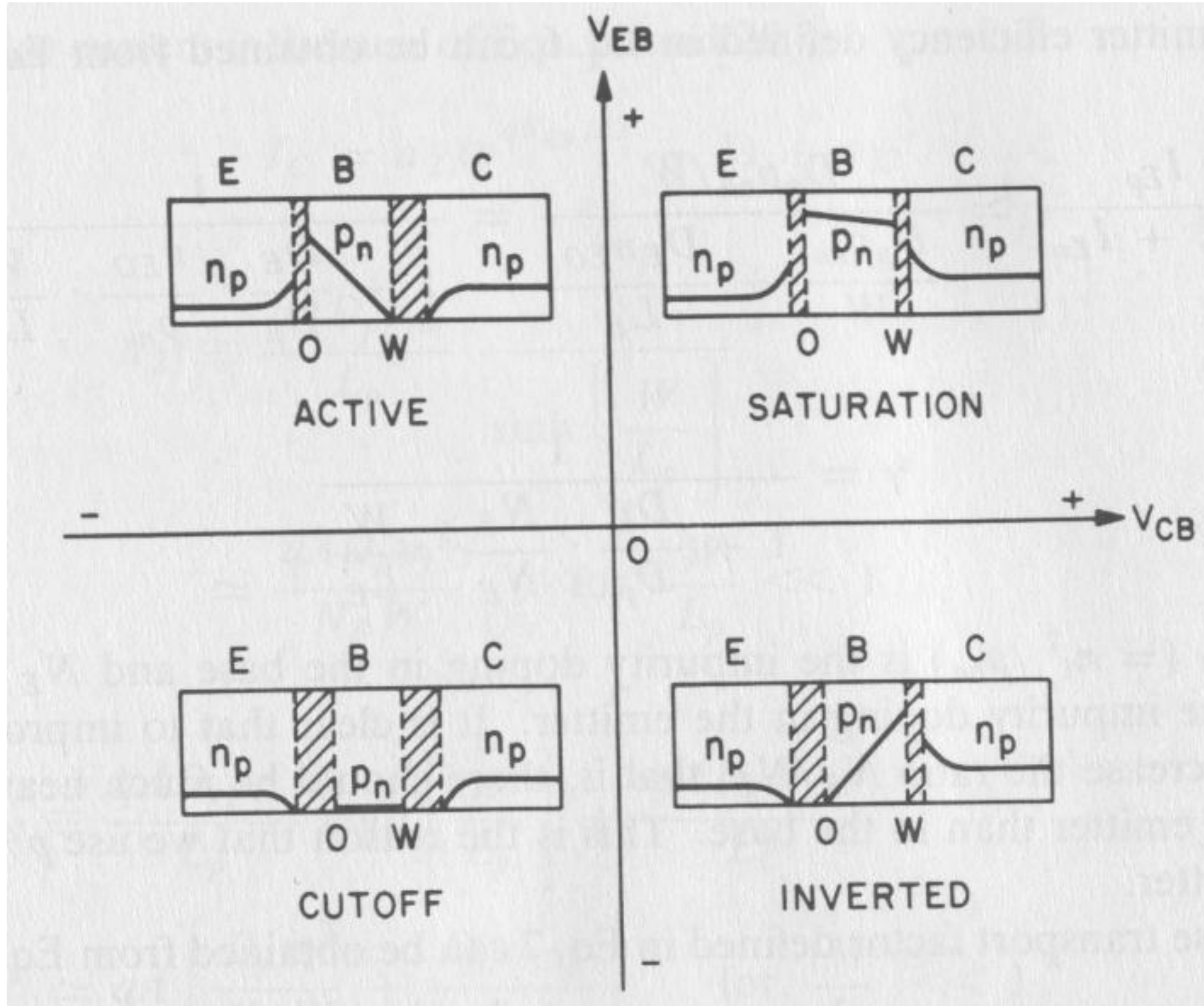


Modes of operation

- A bipolar transistor has four modes of operation depending on the voltage polarities on the emitter-base junction and the base collector junction.
  - **Active mode**: The emitter-base junction is forward biased and the collector-base junction is reverse biased.
  - **Saturation mode**: Both junctions are forward biased. Corresponds to a small biasing voltage and large output current (acts as a switch in ON mode).
  - **Cutoff mode**: Both junctions are reverse biased. There is virtually no charge stored in the base region, the collector current approaches zero (acts as a switch in OFF mode).
  - **Inverted mode**: The emitter-base junction is reverse biased and the collector base junction is forward biased. Corresponds to the case where the collector acts like an emitter and the emitter acts like a collector.

Modes of operation

Minority carrier distributions in various regions of an *n-p-n* transistors in various modes of operation.



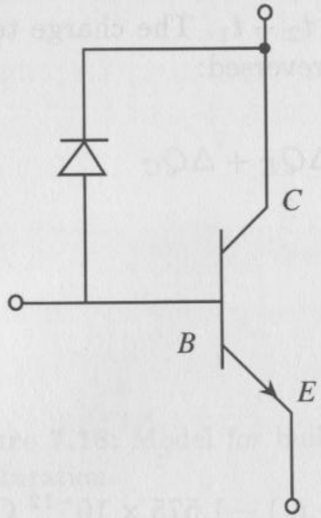
Schottky transistor

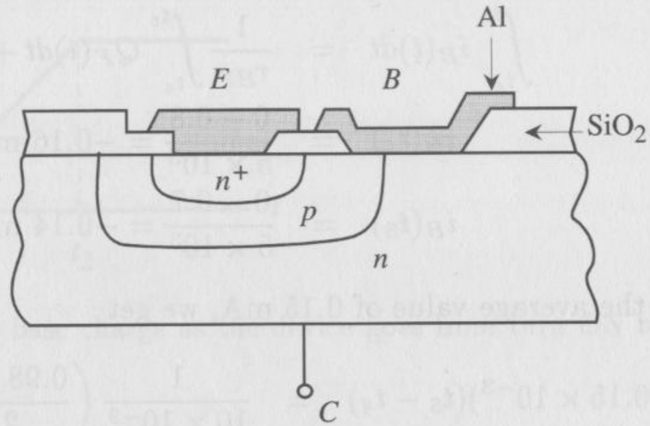
- The Schottky diode is a majority carrier device, which means its transient response is much faster than that of bipolar devices.
- The properties of the Schottky diode are used to speed up the response of the BJT.
- The metal makes an Ohmic contact to the base, but forms a Schottky barrier on the collector.
  - When the transistor is in cutoff (or active) mode, the base collector and the Schottky diode are reverse biased. The Schottky diode thus has no influence on the device.
  - When the transistor starts to go to saturation, the diode becomes forward biased and the voltage across the base-collector is clamped to the forward ON-bias of the diode.

Schottky transistor

- The turn-ON voltage of the Schottky diode is much smaller than that of the base-collector junction. The diode allows the excess base current to pass through it.
- The device will therefore not go into saturation mode and the extraction of the excess charge becomes fast.
- The device can now be switched in a much shorter time.
- The faster switching of the Schottky-clamped device arises from the time needed to remove saturation charge during device turn-OFF.
- The Schottky transistor is an important component of the non-saturated bipolar logic and is used in applications where speed is important.

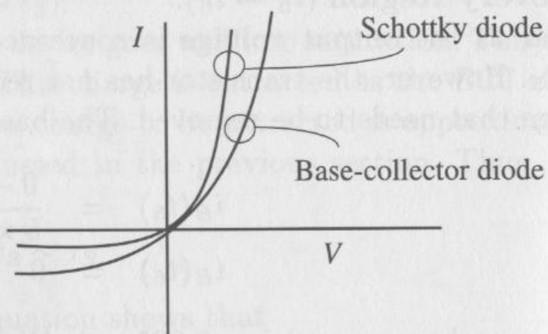
Schottky transistor





Al makes an ohmic contact to the *p*-type base and a Schottky contact to the *n*-type collector

- Collector-Base reverse biased
  Schottky diode is reverse biased
- Collector-Base forward biased
  Schottky diode turns ON and collector is bypassed

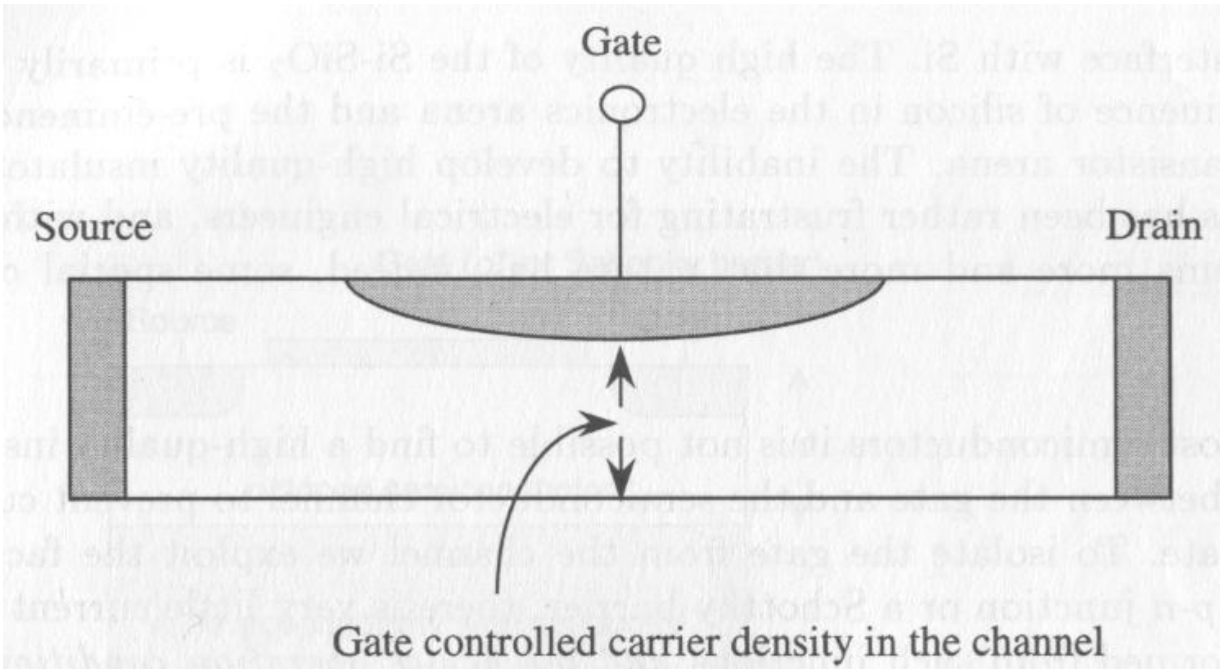


Schottky diode is turned ON at a voltage smaller than what it takes the CBJ to be in the saturated mode

Field Effect Transistors

- The **field effect transistor** is the most important electronic device in modern solid state technology.
- The first transistors were based on the bipolar concept and because of poor quality Si-SiO_2 interfaces, FETs could not compete.
- As the interface quality improved, many of the BJT functions were replaced by metal-oxide semiconductors FET (MOSFET).
- New kinds of FETs based on material like GaAs have now been fabricated. These metal semiconductor FETs are called MESFETs

FET: Principles



- The gate alters the charge drifting from the source to the drain.
- As the gate potential changes the current flow is altered.

Field Effect Transistor: Basics

- The device consists of an active channel through which electrons flow from the source to the drain. The source and the drain are **Ohmic contacts**. The conductivity of the channel is modulated by a potential applied to the gate.
- The gate must be isolated from the current flow in order that it doesn't draw current and hence does not produce a poor gain.
  - The gate isolation is done in a variety of ways. In the **MOSFET** the gate is isolated from the channel by an oxide.
  - In the metal semiconductor **FET** (**MESFET**), the gate forms a Schottky barrier with the semiconductor and the gate current is small in the useful range of gate voltages.
  - In the junction **FET** or **JFET** a *p-n* junction is used in reverse bias to isolate the gate.

FET: Classifications

- FETs can be divided into two main groups.
  - Devices where the gate isolation is achieved by the use of an insulator between the gate and the active channel where the electron flow occurs. If the insulator bandgap is large, electrons can be "induced" into the channel without any doping.
  - Devices where the gate isolation is achieved by using a Schottky barrier or *p*-*n* junction. Dopants are used to provide free carriers and the gate serves to alter the channel conductivity by changing the depletion width.
- The gate isolation technology is a key ingredient of the FET in all these configurations.

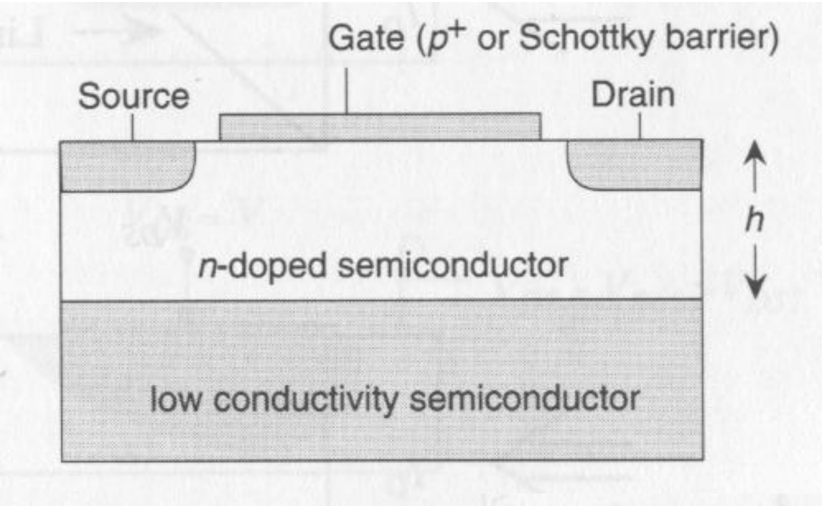
The JFET and MESFET

- For most semiconductors it is not possible to find a high-quality insulator that can be placed between the gate and the semiconductor channel to prevent current leakage into the gate.
- To isolate the gate from the channel the feature that in a reverse biased p-n junction or Schottky barrier, there is very little current flow.
- If a gate is formed from such a junction the gate-semiconductor junction must always be reverse biased.
- The gate can then modulate the depletion region under it and thus control the conductivity of the semiconductor channel.

The JFET and MESFET

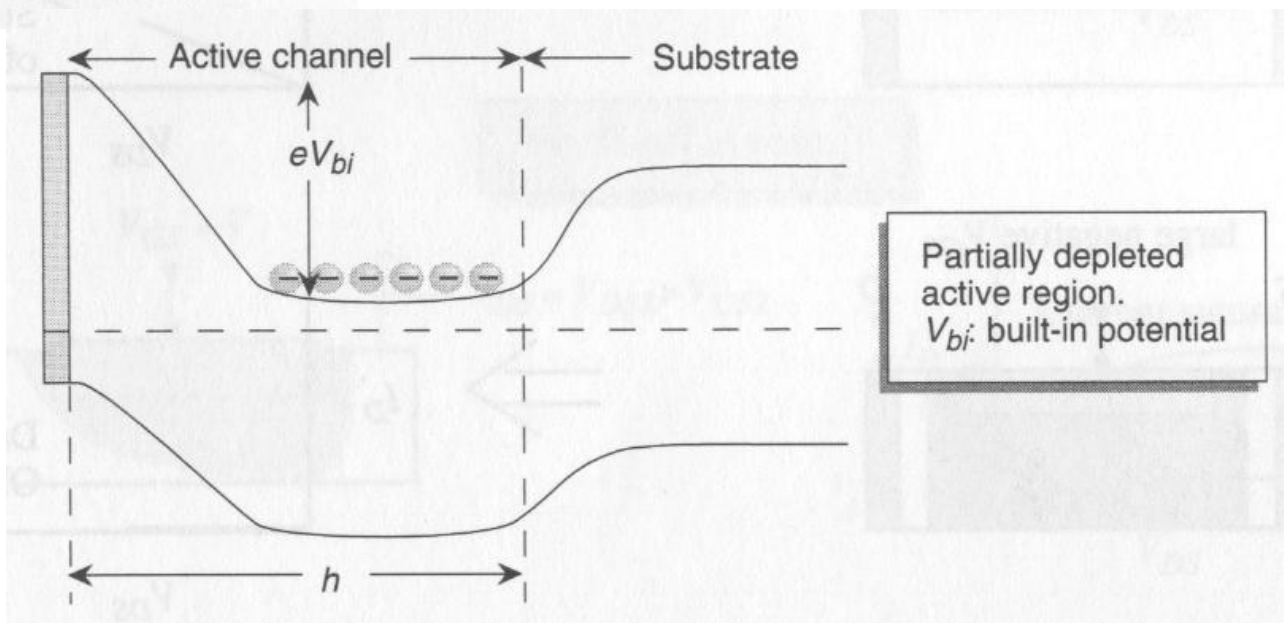
- The simplest field effect transistor is the junction FET (JFET).
- The main difference between the JFET and the MESFET is that the JFET is based on a p-n junction while the MESFET is based on a Schottky barrier diode.
- As you might imagine the JFET is not used as widely as the MESFET.
- Recall that the reverse current in a Schottky junction is much larger than that in a p-n junction, as a result the JFET is especially used in materials for which it is difficult to produce a large Schottky barrier.
- The device is based on a low conductivity substrate on which a n-type region is grown.

The JFET and MESFET



Schematic of JFET

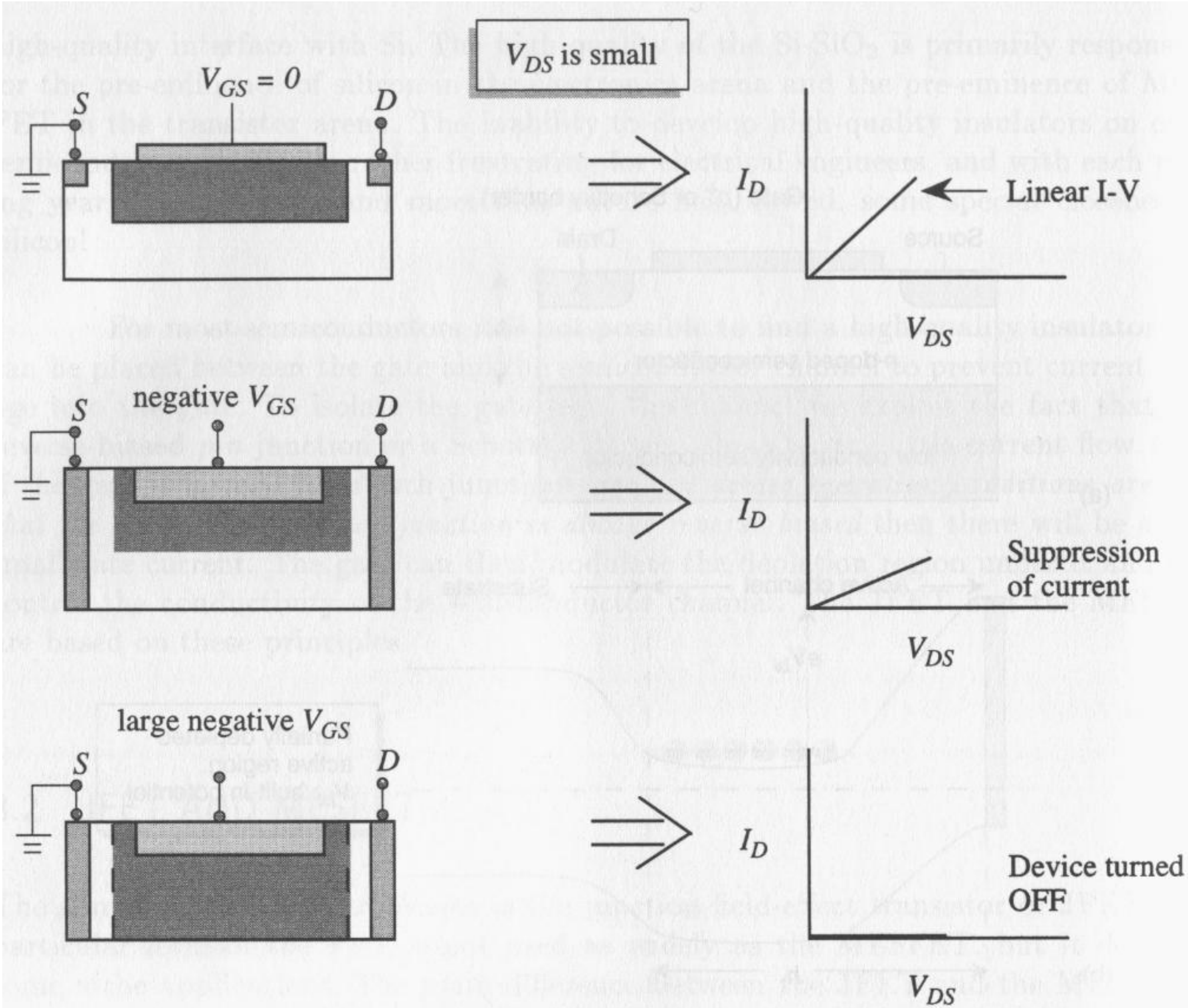
Band profile when applied gate bias and source drain bias are zero



The JFET and MESFET

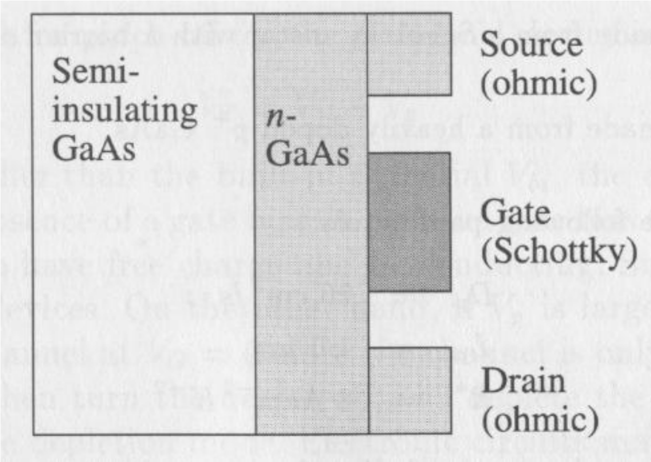
- The source and drain are **Ohmic contacts**
- A negative bias on the gate reverse biases the gate-ohmic conductor junction and alters the width of the depletion region.
- This allows the gate to modulate the conductance of the device.
- For a small source-drain bias V_{DS} and no gate bias, as the gate bias is increased and the gate semiconductor junction is reverse biased, the current through the channel decreases.
- This will continue until the channel is “pinched off”.

JFET/MESFET under zero bias



MESFET: Remarks

- The MESFET is a relatively simple device to fabricate. Common materials used are GaAs and InP.
- The substrate material for the GaAs MESFET is high-resistivity semi-insulating GaAs.
- The active region of the device is made by an n-channel that is produced by epitaxial processes or ion implantation.
- The source and drain contacts or Ohmic and the gate is formed by a Schottky barrier.



FET: The MOSFET

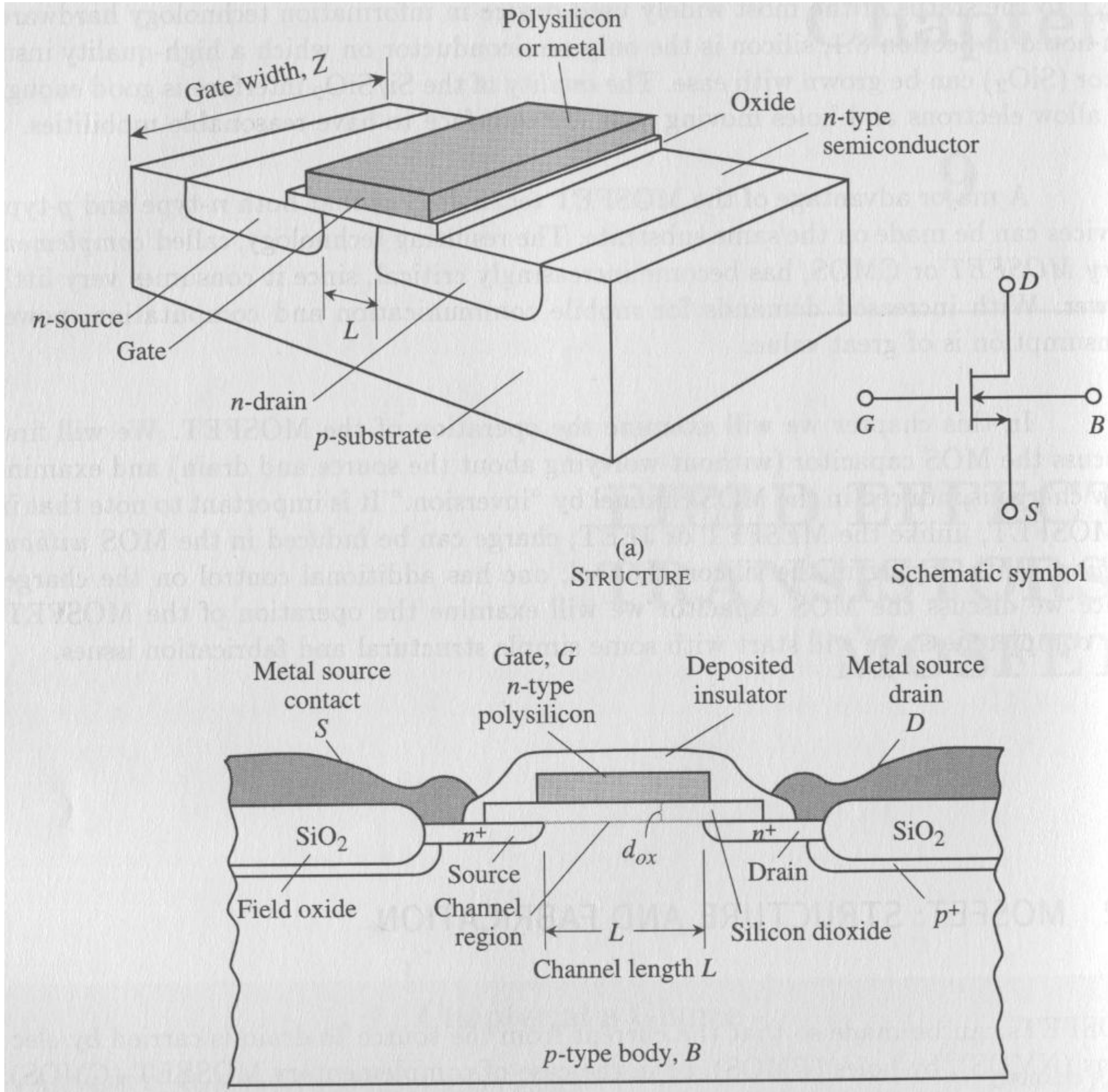
- The Si-based FETs use the MOSFET concept while most III-V compound semiconductors are based on the MESFET or JFET concepts.
- In the MOSFET free carriers are produced in a channel by the process of “inversion” where a gate pulls the bandedges to a point lower than the Fermi level and thus creates free carriers.
- This requires excellent insulation between the gate and the channel.
- There should therefore be a high bandgap semiconductor material separating the gate and the channel, otherwise there will be a large current between the gate and the channel.
- For Si the insulator is SiO_2 the high quality interface between these material is primarily responsible for the dominance of Si in electronic components and the predominance of MOSFETs.

The MOSFET and CMOS

- High yield, low cost and dense packing are considerations that have pushed the MOSFET to be the most widely used device in information technology hardware.
- A major advantage of the MOSFET is that both n-type and p-type devices can be made on the same substrate.
- Complementary MOSFETs or CMOS has become increasingly critical since it consumes very little power.
- In a MOSFET, charge can be induced in the MOS without doping (unlike the MESFET or JFET).
- In MOSFETs the current from the source to drain can be carried by electrons (NMOS) or holes (PMOS) or both in CMOS.
- NMOS has a *p*-type substrate

FET: The MOSFET (NMOS)

NMOS device schematic



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