# Introduction

to

# Semiconductor Devices

# Broad courses in electronic engineering

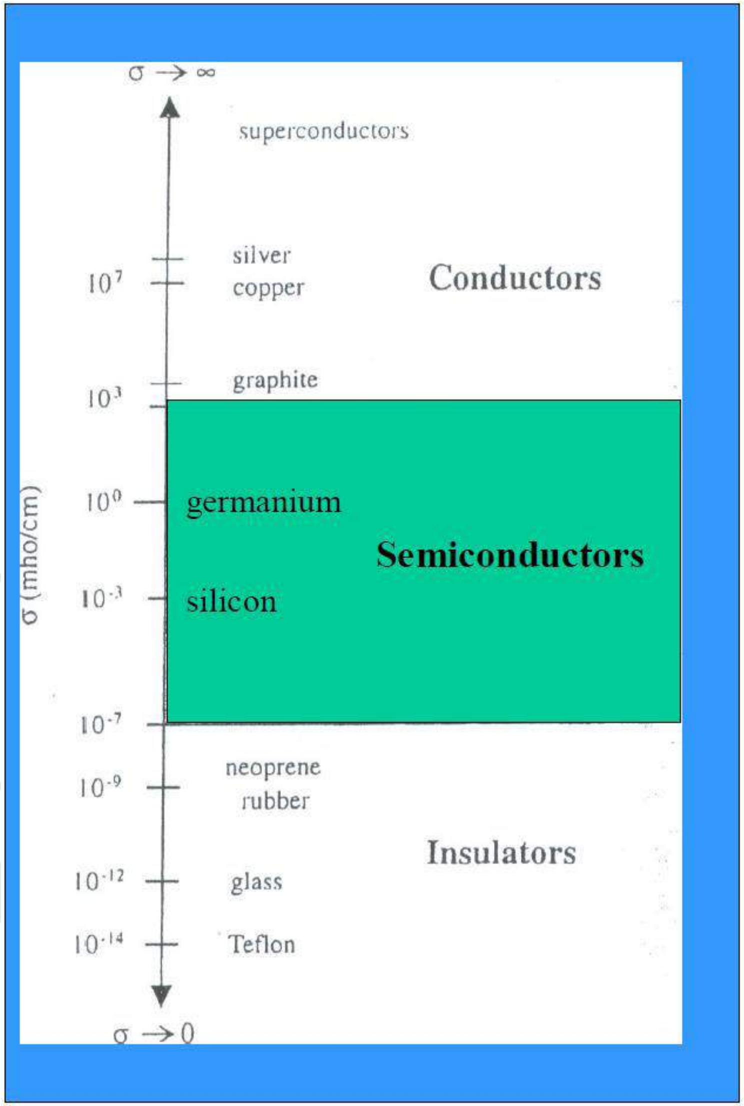
- Semiconductor devices
- Analog circuits
- Digital logic design and circuits
- Microprocessor
- Microelectronic devices, technology and circuits

# Electricity

- Electricity is the flow of electrons
- Good conductors (copper) have easily released electrons that drift within the metal
- Under influence of electric field, electrons flow in a current
- Magnitude of current depends on magnitude of voltage applied to circuit, and the resistance in the path of the circuit
- Current flow governed by Ohm's Law

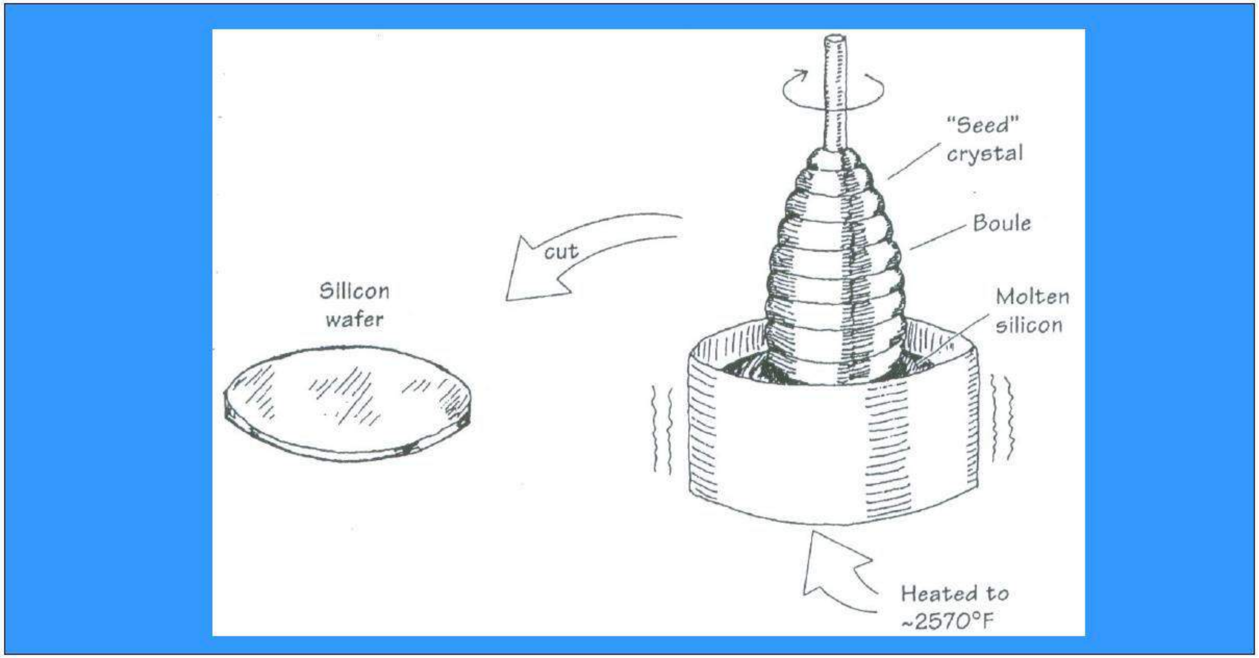
# Semiconductors

- Materials that permit flow of electrons are called conductors (e.g., gold, silver, copper, etc.).
- Materials that block flow of electrons are called insulators (e.g., rubber, glass, mica, etc.).
- Materials whose conductivity falls between that of conductors and insulators are semiconductors.
- Semiconductors are "part-time" conductors whose conductivity can be controlled.



# Semiconductors

- Silicon (Si) is the most common material used to build semiconductor devices.
- Si is spun and grown into a crystalline structure and cut into wafers to make electronic devices.



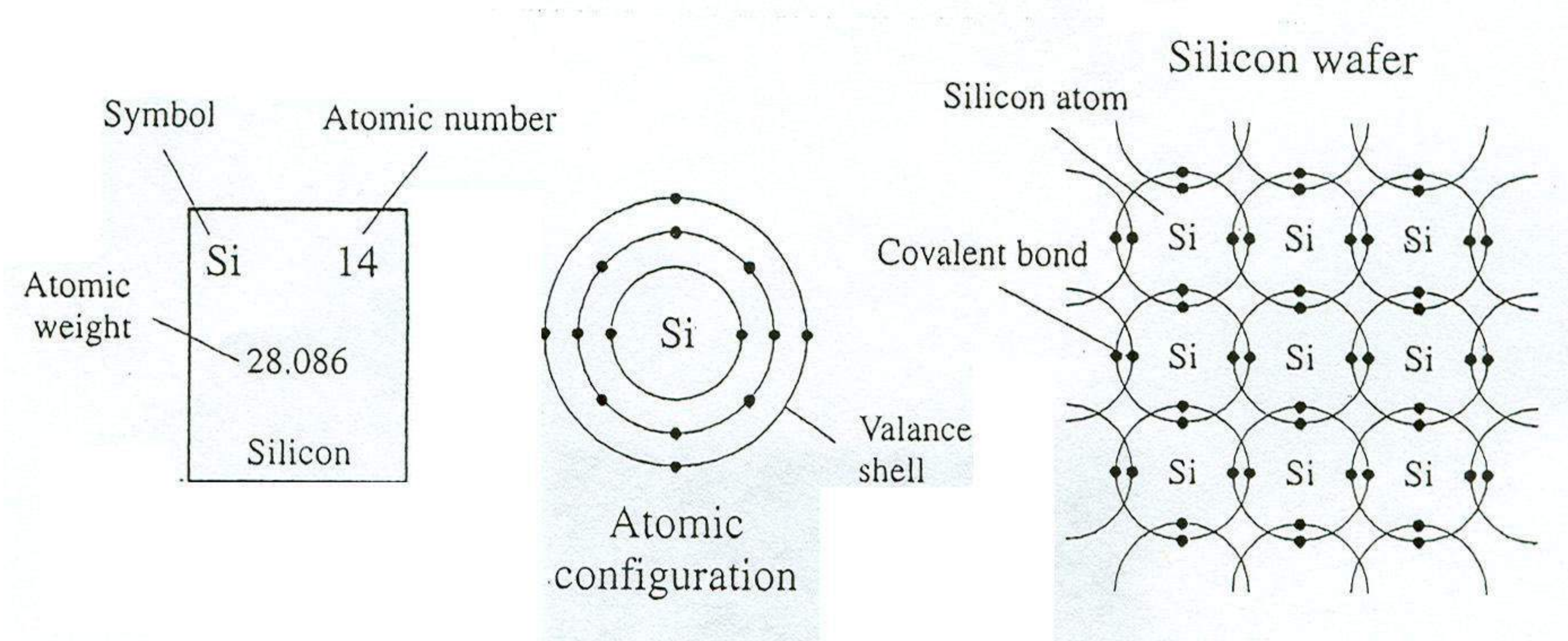
# Electron Bands

- Electrons circle nucleus in defined shells
  - K 2 electrons
  - L 8 electrons
  - M 18 electrons
  - N 32 electrons
- Within a shell, electrons are further grouped into subshells
  - s 2 electrons
  - p 6 electrons
  - d 10 electrons
  - f 14 electrons

# Semiconductor crystalline structure

- Semiconductors (Si, Ge) have 4 electrons in their outer shell
  - 2 in the s subshell
  - 2 in the p subshell
- Si has 14 electrons: 2 K, 8 L, 4 M
- Ge has 32 electrons: 2 K, 8 L, 18 M, 4 N
- Inner electrons are very closely bound to atom
- Outer shell electrons (called valence electrons) are shared with neighbor atoms on both sides to "fill" the shell

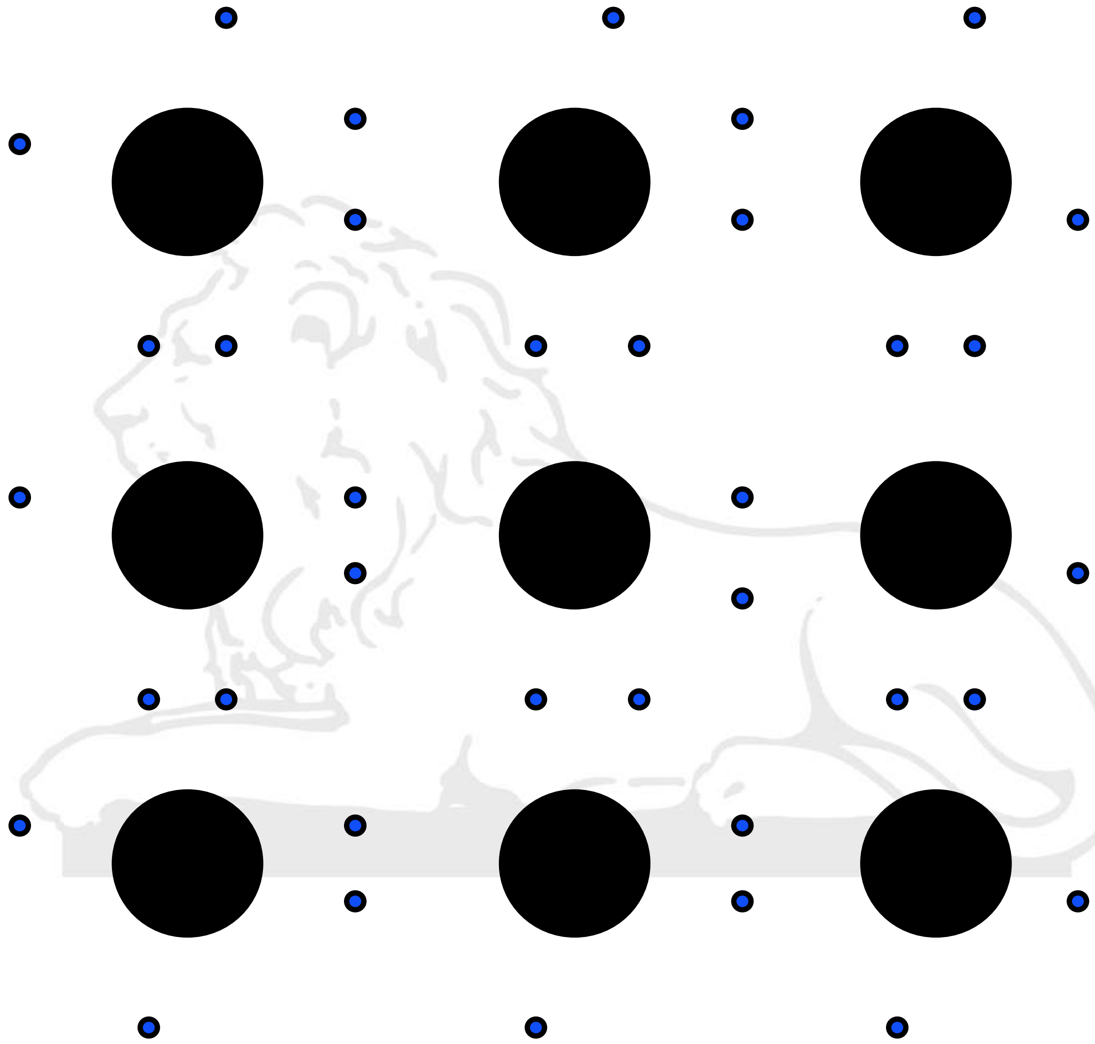
# Semiconductor crystalline structure



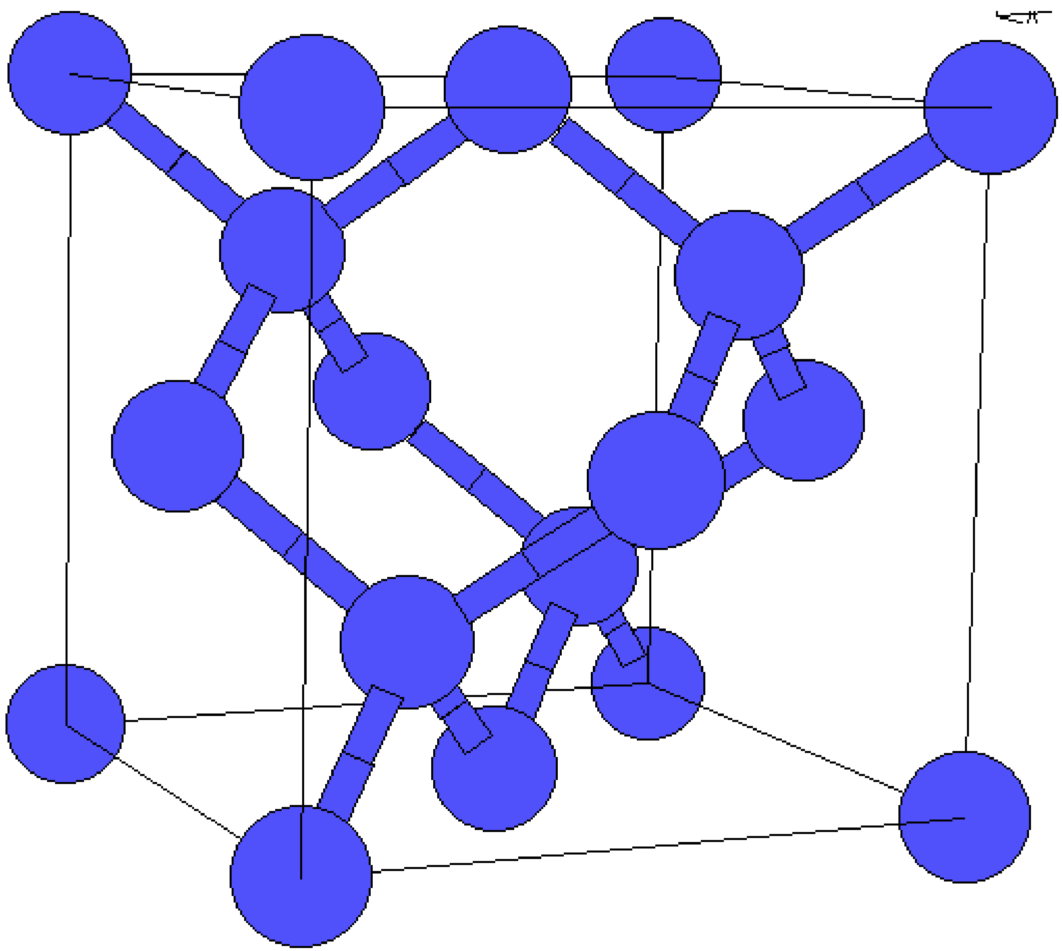
# Semiconductor crystalline structure

- In the crystalline lattice structure of Si, the valence electrons of every Si atom are locked up in covalent bonds with the valence electrons of four neighbouring Si atoms.
  - resulting structure is very stable
- In pure form, electrons are fairly tightly bound; no "loose" electrons – Si wafer does not contain any free charge carriers.
- At room temperature, an applied voltage across pure Si wafer does not yield electron flow through the wafer; or very little electric current flows
  - A pure Si wafer is said to act almost as an insulator.

# Semiconductor crystalline structure



# Semiconductor crystalline structure

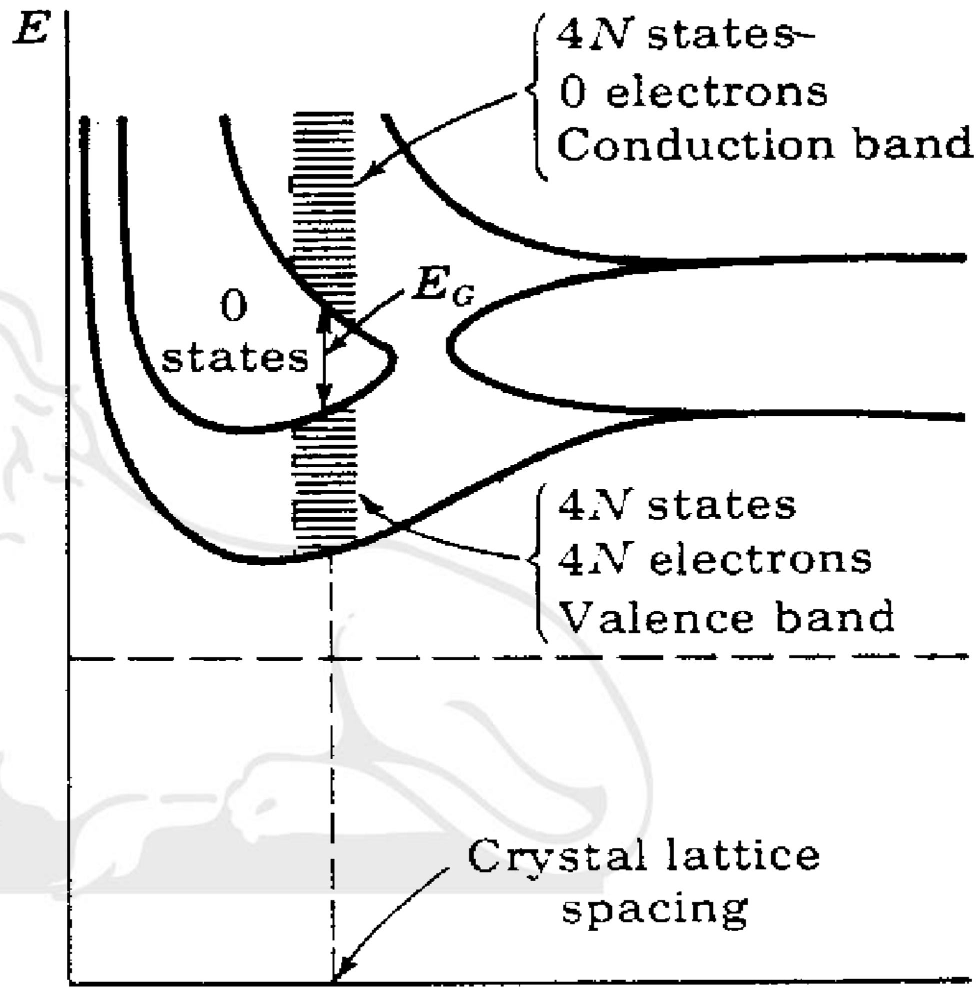


# Energy bands in semiconductors

- As the distance between atoms decreases the discrete subshells spread out into bands
- As the distance decreases further, the bands overlap and then separate
  - the subshell model doesn't hold anymore, and the electrons can be thought of as being part of the crystal, not part of the atom
  - 4 possible electrons in the lower band (valence band)
  - 4 possible electrons in the upper band (conduction band)

# Energy bands in semiconductors

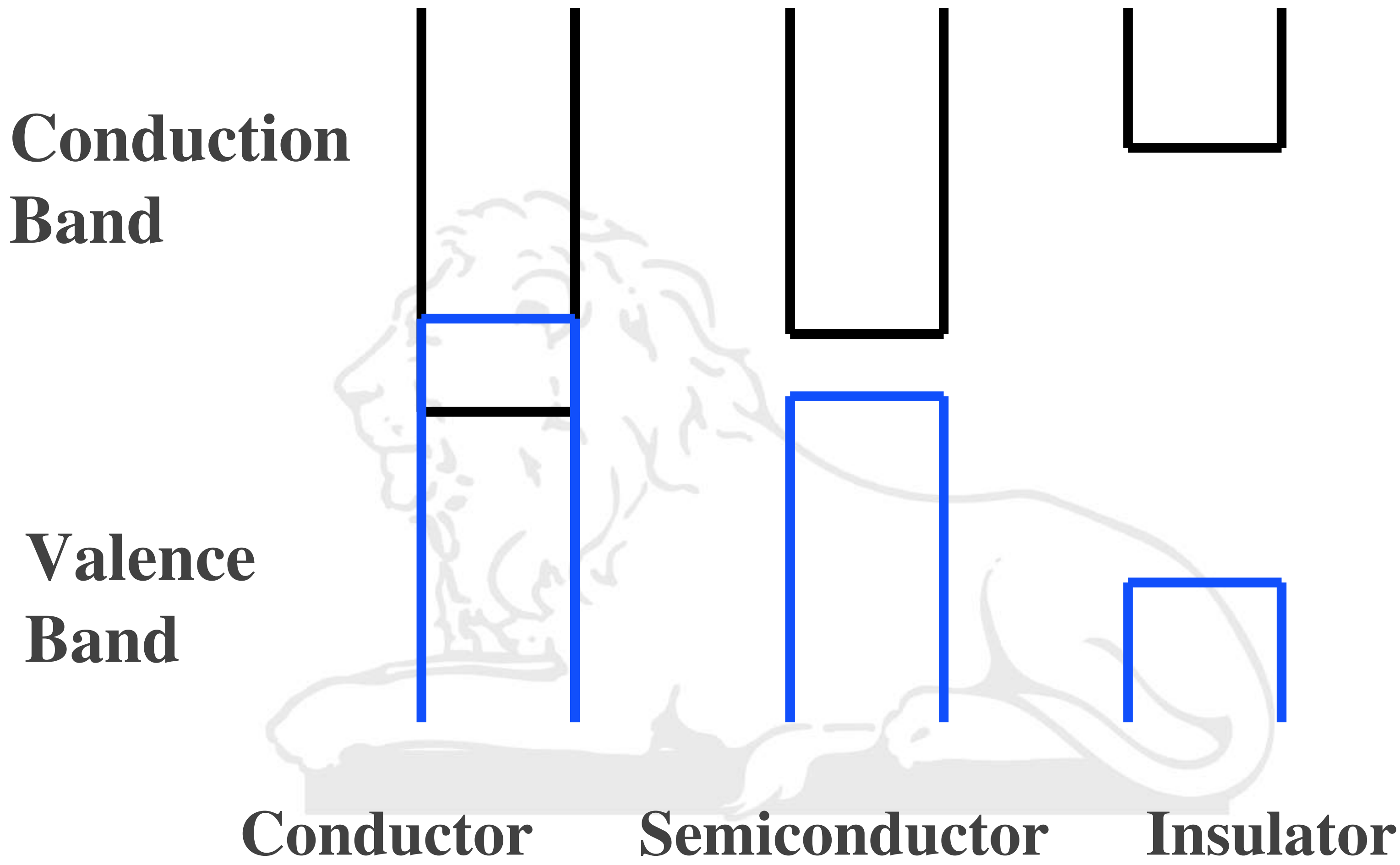
- The space between the bands is the energy gap, or forbidden band
- This separation of the valence and conduction bands determines the electrical properties of the material



# Energy bands in semiconductors

- Insulators have a large energy gap
  - electrons can’t jump from valence to conduction bands
  - no current flows
- Conductors (metals) have a very small (or nonexistent) energy gap
  - electrons easily jump to conduction bands due to thermal excitation
  - current flows easily
- Semiconductors have a moderate energy gap
  - only a few electrons can jump to the conduction band leaving “holes”
  - only a little current can flow

# Energy bands in semiconductors



# Conduction in conductors

- The key to electrical conductivity in an element is the number of electrons in the valence band.
- Some atoms of a conductor have only one electron in the outer orbit which can be easily dislodged by application of voltage across the element. Even slightest voltage can cause these electrons to flow from one atom to another.
- These freely flowing electrons do not belong to any specific atom and are called free electrons or conduction band electrons.
- Insulators can have up to eight electrons in the outer shell that are tightly bound to its atom, hence no freely flowing electrons.

# Current in semiconductors

- Conductivity of semiconductor depends on the density of free charge carriers.
- Density of free charge carriers (electrons) is approximately constant in conductors and insulators.
- In semiconductors, it is possible to manipulate the density of free charge carriers.
- This feature is significant in controlling the flow of current through a semiconductor.

# Current in semiconductors

- Semiconductor devices are negative temperature coefficient devices – resistance decreases with increase in temperature

- Note that resistance of conductors decrease with decrease in temperature – superconductivity at absolute zero.

- On the other hand, semiconductors behave as insulators at absolute zero and as conductors at higher temperature.

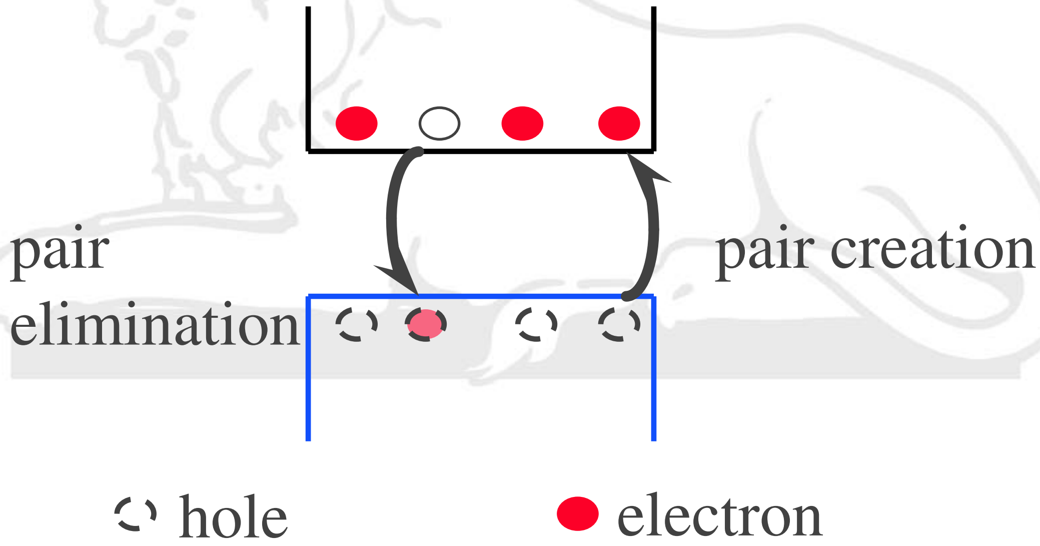
- Higher the ambient temperature, more is the vibration of atoms in the semiconductor lattice dislodging more electrons from valence band.

- This generates electron-hole pairs.

# Hole-electron pairs

- Sometimes thermal energy is enough to cause an electron to jump from the valence band to the conduction band – produces a hole-electron pair

- Electrons also “fall” back out of the conduction band into the valence band, combining with a hole



# Hole-electron pairs

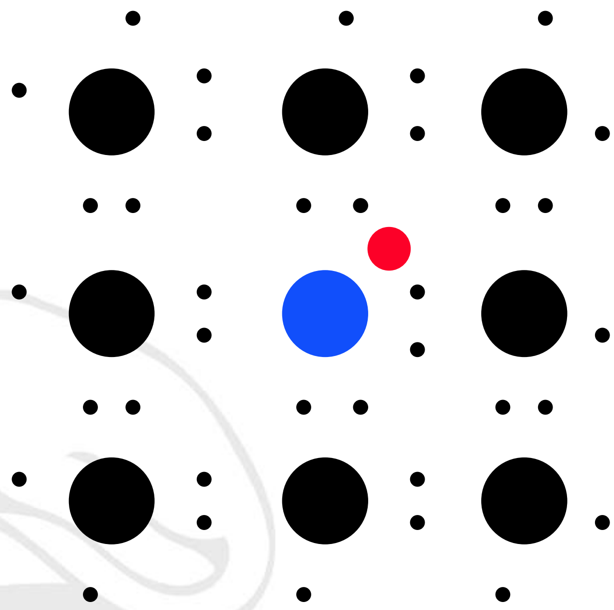
- Conduction takes place by hole-electron pair generation and recombination.
- So, flow of current in semiconductor is due to flow of both electrons (negative charge carriers in conduction band) and holes (positive charge carriers in valence band).
- If external voltage is applied, free electrons move towards positive terminal while holes move towards negative terminal.
- At room temperature, semiconductors have only few thermally generated free electrons.
- One way to raise conductivity in semiconductor is to increase hole/electron concentration by doping

# Extrinsic semiconductors

- To make semiconductors better conductors, add impurities (dopants) to contribute extra electrons or extra holes
  - elements with 5 outer electrons contribute an extra electron to the lattice (donor dopant)
  - elements with 3 outer electrons accept an electron from the silicon (acceptor dopant)
- Therefore, appropriate impurities are from the 3rd and 5th columns of the periodic table.
- A pure semiconductor is called intrinsic semiconductor while a doped semiconductor is called extrinsic semiconductor.

# Extrinsic semiconductors

- Pentavalent impurities such as phosphorus, arsenic, antimony and bismuth have 5 valence electrons.
- When phosphorus impurity is added to Si, every phosphorus atom's four valence electrons are locked up in covalent bond with valence electrons of four neighbouring Si atoms.
- The 5th valence electron of phosphorus atom does not find a binding electron and thus remains free to float.

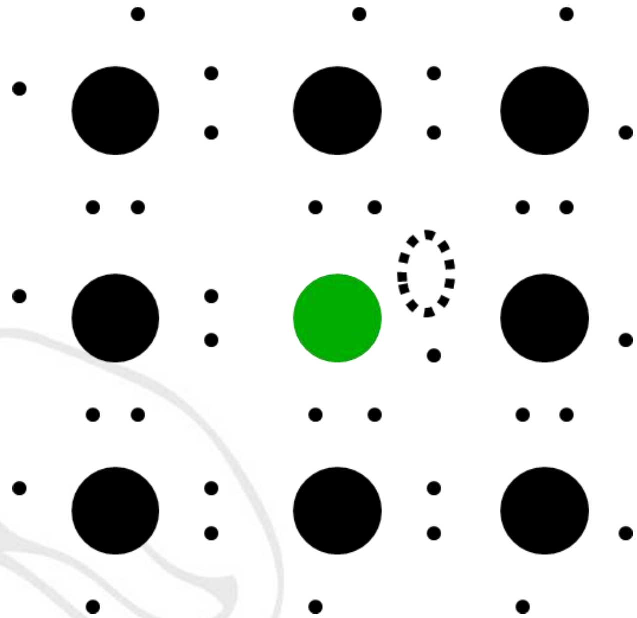


# Extrinsic semiconductors

- This extra electron is very loosely bound to atom and can easily jump to conduction band, hence “free” to move around and contribute to electric current.
- When a voltage is applied across Si-Phosphorus mixture, free electrons migrate toward the positive voltage end.
- The pentavalent impurities are referred to as donor impurities – a pentavalent atom becomes positively charged by donating one electron
- Produces n-type extrinsic semiconductor
  - Electrons are the majority carriers (more in number)
  - Holes are the minority carriers.

# Extrinsic semiconductors

- Trivalent impurities e.g., boron, aluminium, indium, and gallium have 3 valence electrons.
- When boron is added to Si, every boron atom's three valence electrons are locked up in covalent bond with valence electrons of three neighbouring Si atoms.
- However, a vacant spot "hole" is created within the covalent bond between one boron atom and a neighboring Si atom.



# Extrinsic semiconductors

- When a voltage is applied across Si-Boron mixture, the electron from neighbouring silicon atom falls into the boron atom filling the hole in boron atom and creating a “new” hole in the silicon atom.
- It appears as if a hole moves toward the negative terminal.
- The trivalent impurities are referred to as acceptor impurities – a trivalent atom becomes negatively charged by accepting one electron.
- Produces p-type extrinsic semiconductor
  - Holes are the majority carriers (more in number)
  - Electrons are the minority carriers.

# Charge drift velocity

Drift velocity of charge carrier $\boxed{v = \mu \mathcal{E}}$

$\mathcal{E}$ = applied electric field (Volt/m)

$\mu$ = mobility of carrier ($m^2$/Volt-sec) = Constant

When electric field is applied, the carrier attains velocity $v$ from rest in time $t$ $\Rightarrow$ $\boxed{v = at}$, $a$ = acceleration

$\boxed{a = q\mathcal{E}/m}$ where $q$ = charge of carrier (Coulomb)

$m$ = mass of carrier (kg)

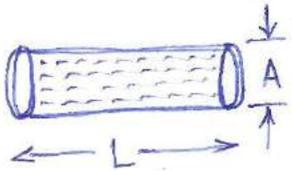
$q\mathcal{E}$ = Force acting on the carrier due to the applied field.

$\therefore$ $\boxed{\mu = qt/m}$ $\Rightarrow$ Time taken to attain the drift velocity

$\boxed{t = \mu m/q}$ = Constant at a given temperature.

# Conductivity and current density

Current Density $\boxed{J = \frac{I}{A} = \frac{1}{A} \times \frac{Nq}{T} = \frac{1}{A} \times \frac{Nqv}{L} = nqv}$ $\boxed{= \rho v \ \left(\text{Amp}/m^2\right)}$




$n$ = carrier density (per $m^3$)

$\rho$ = charge density $\left(\text{Coulomb}/m^3\right)$

Using relation for drift velocity : $\boxed{J = \rho \mu \mathcal{E} = \sigma \mathcal{E} = nq\mu \mathcal{E}}$

$\boxed{\sigma = \rho \mu = nq\mu}$ ⟵ Conductivity of the conductor in $(\text{Ohm-m})^{-1}$

In semiconductor :

$$\boxed{\begin{aligned} J &= (n\mu_n + p\mu_p)\, q \mathcal{E} \\ \sigma &= (n\mu_n + p\mu_p)\, q \end{aligned}}$$

$n$ = free-electron concentration

$p$ = hole concentration.

# Charge carrier concentrations

- In intrinsic semiconductor
  - Electron-hole pairs are generated by thermal energy
  - Let, no. of electron-hole pairs at any instant of time be $\boxed{n = p = n_i}$, $n_i$ is called the intrinsic concentration.
  - By mass-action law, the product of free-electron and hole concentration is always constant at a given temperature.
  - Therefore, $\boxed{np = n_i^2}$ $\rightarrow n_i$ turns out to be constant at a given temperature

# Charge carrier concentrations

<u>n-type semiconductor</u> : $N_D$ = Doping concentration (donor atoms)

$\Rightarrow$ $N_D$ number of free-electrons leaving same number of positive ions

No. of electron-hole pairs generated $n = p$

Total positive-charge concentration $= N_D + p$

out of which hole concentration $p_n = p$

Total negative-charge concentration $= N_D + n$

out of which free-electron concentration $\boxed{n_n = N_D + n \approx N_D}$

By mass-action law : $n_n p_n = n_i^2 \rightarrow (N_D + n) p = n_i^2$

$$\Rightarrow \boxed{p_n \approx \frac{n_i^2}{N_D}}$$

# Charge carrier concentrations

p-type semiconductor: $N_A$ = Doping concentration (acceptor atoms)

$\Rightarrow N_A$ number of holes forming same number of neg. ions.

Total negative charge concentration $= N_A + n$

out of which free-electron concentration $n_p = n$

Total positive charge concentration $= N_A + p$

out of which hole concentration $\boxed{p_p = N_A + p \approx N_A}$

By mass-action law: $(N_A + p)n = n_i^2 \rightarrow n_p p_p = n_i^2$

$$\Rightarrow \boxed{n_p \approx \frac{n_i^2}{N_A}}$$

# Conductivity of extrinsic semiconductor

- To produce reasonable levels of conduction doesn't require much doping
  - silicon has about 5 x $10^{22}$ atoms/cm$^3$
  - typical dopant levels are about $10^{15}$ atoms/cm$^3$
- Conductivity of n-type semiconductor:

$$\boxed{\sigma_n = (n_n\mu_e + p_n\mu_h)q = \left(N_D\mu_e + \frac{n_i^2}{N_D}\mu_h\right)q}$$

- Conductivity of p-type semiconductor:

$$\boxed{\sigma_p = (n_p\mu_e + p_p\mu_h)q = \left(\frac{n_i^2}{N_A}\mu_e + N_A\mu_h\right)q}$$

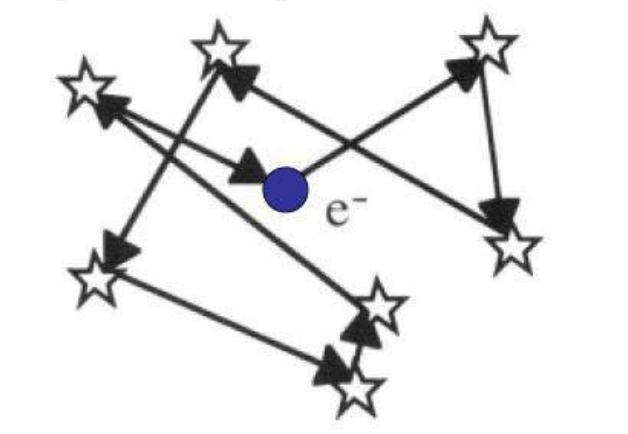
# Some useful data for Ge and Si

| Physical quantity | Unit | Ge | Si |
|---|---|---|---|
| Atomic Number | | 32 | 14 |
| Atomic weight | | 72.6 | 28.1 |
| Density | $g/cm^3$ | 5.32 | 2.33 |
| Atomic concentration | per c.c. | $4.4 \times 10^{22}$ | $5.0 \times 10^{22}$ |
| Band gap $E_{GO}$ at $0°K$ | eV | 0.785 | 1.21 |
| Band gap $E_G$ at $300°K$ | eV | 0.72 | 1.10 |
| Intrinsic concentration $n_i$ at $300°K$ | per c.c. | $2.5 \times 10^{13}$ | $1.5 \times 10^{10}$ |
| Electron mobility $\mu_n$ at $300°K$ | $cm^2/V\text{-}s$ | 3800 | 1300 |
| Hole mobility $\mu_p$ at $300°K$ | $cm^2/V\text{-}s$ | 1800 | 500 |

# Electron transport phenomenon

- Electrons in the conduction band can freely move along the crystal (hence called free-electrons) but experiences frequent collisions with atoms.

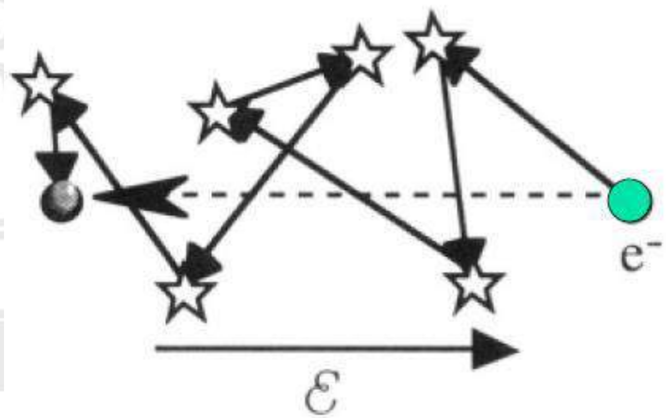
- As a result it moves randomly with velocity of about $10^5$ m/s.




- When no electric field is applied, on average the electron does not go anywhere (equilibrium condition) and average electric current is equal to zero.

# Electron transport phenomenon

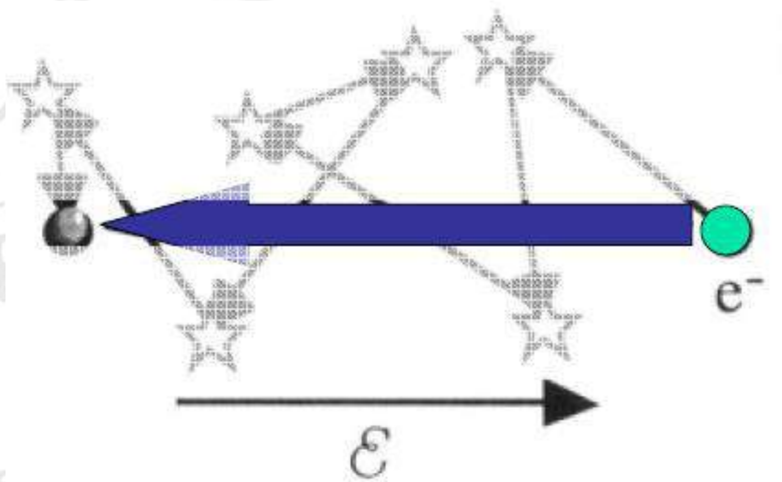
- When electric field is applied, an electric force $F = -q\mathcal{E}$ acts on any free-electron in a direction opposite to field direction.
- Electron still experiences frequent random collisions.
- However, after each collision the electron's velocity has a component toward the positive electrode.




- On average, the electron drifts from negative electrode toward positive resulting in a current through the conductor.

# Electron transport phenomenon

- Ignoring the collisions, which are completely random, we can say that **average electron velocity (drift velocity) is proportional to the electric field applied** **(** $v = \mu\mathcal{E}$ **).**




- In conductors, the atom-to-atom interactions free up valence electrons from each atom (valence band and conduction band overlap) → concentration of free electron high → high conductivity **(** $\sigma = nq\mu$ **).**

# Electron transport phenomenon

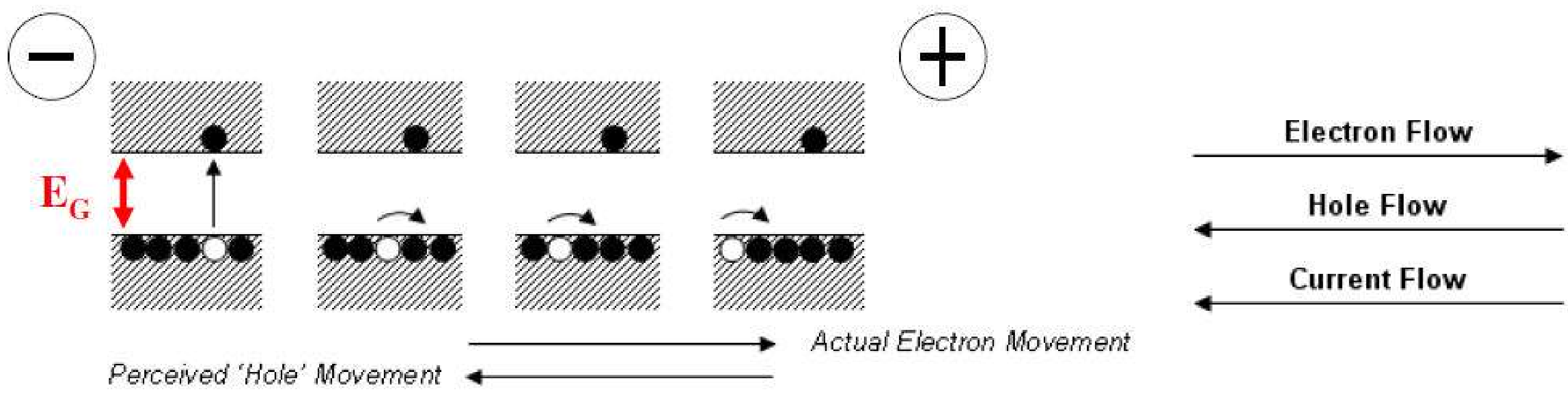
- In insulators, no free electrons → zero conductivity.
- In semiconductor, if ambient temperature is high enough the crystal lattice vibrates and delivers extra energy to electrons.
- Some electrons acquire high enough energy to move from valence band to conduction band to become free electrons.
- When electric field is applied, these free electrons contribute to one component of current in the same way as in case of conductors.
- Since only few atoms can donate free electrons, its concentration is not as high as in conductors → less conductivity.

# Hole transport phenomenon

- A hole is created when an atom frees an electron.
- The concept of holes is introduced because it is easier to keep track of the missing electrons in an "almost-full" band, rather than keeping track of the actual electrons in that band.
- Holes are missing electrons. They behave as particles with the same properties as the electrons would have occupying the same states except that they carry a positive charge.
- In short, holes are virtual positively charged particles.

# Hole transport phenomenon

- In the presence of an external electric field, electrons in valence band move from an atom to a nearby one without jumping into the conduction band, thereby filling a hole "near to them“ while leaving a hole "behind them".
- This is perceived as hole moving in a direction opposite to the direction in which the electrons actually move in the valence band.



# Hole transport phenomenon

- This *virtual* movement of holes in the valence band contributes to the other component of current which is not observed in conductors.

- In actual, both the current components are due to movement of electrons.

- The 'hole' is an abstraction; it has no substance and does not actually move itself.

- Valence electrons are more tightly bound to atoms and hence their movement are sluggish and slow.

- This accounts for lower mobility of holes.

# pn-junction

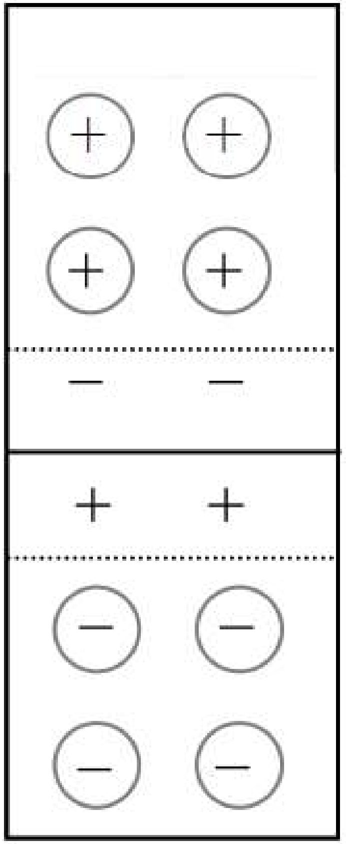
- A pn-junction is formed by joining together n-type and p-type semiconductors.
- The area between the p-type and n-type portion is called the pn-junction.
- It is characterized by changing of doping from p-type to n-type.
- In practice, as the n-type Si crystal is being grown, the process is abruptly altered to grow p-type Si crystal. Finally, a glass or plastic coating is placed around the joined crystal.
- The p-side is called anode and the n-side is called cathode.

# pn-junction

- When a p-type and an n-type substances are placed in contact, free electrons from n-type diffuses into p-type; holes flow in the reverse direction.
- A potential difference is created at the junction → positive potential at n-type side and negative potential at p-type side.
- This is called potential barrier.
- Electron diffusion stops when this potential barrier is high enough to repel further transfer of electrons / holes.
- Typical values of potential barrier in case of silicon and germanium are 0.7 V and 0.3 V, respectively.

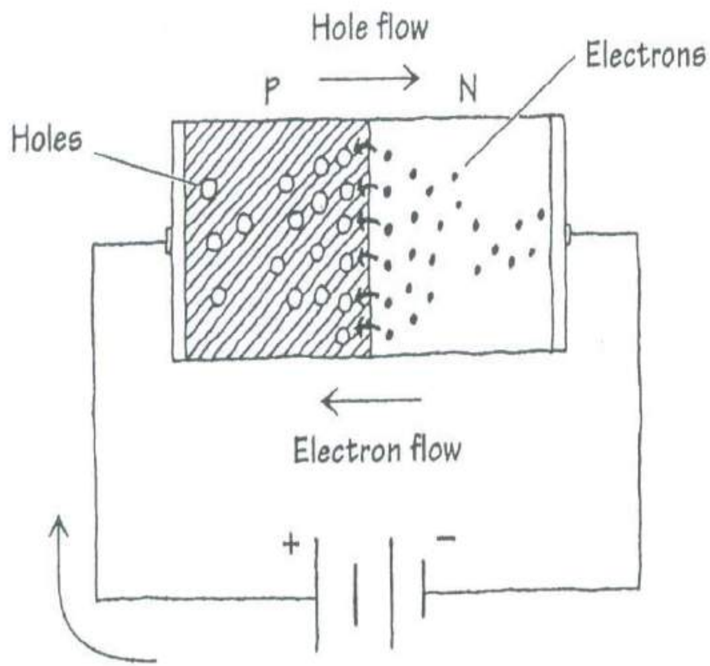
# pn-junction

- As a result, the region at the junction becomes devoid of any charge carriers.
- That is, the region is depleted of free electrons at n-type side and holes at p-type side.
- This region is called depletion layer.
- This depletion region acts as an insulator preventing flow of charges to and from either sides.



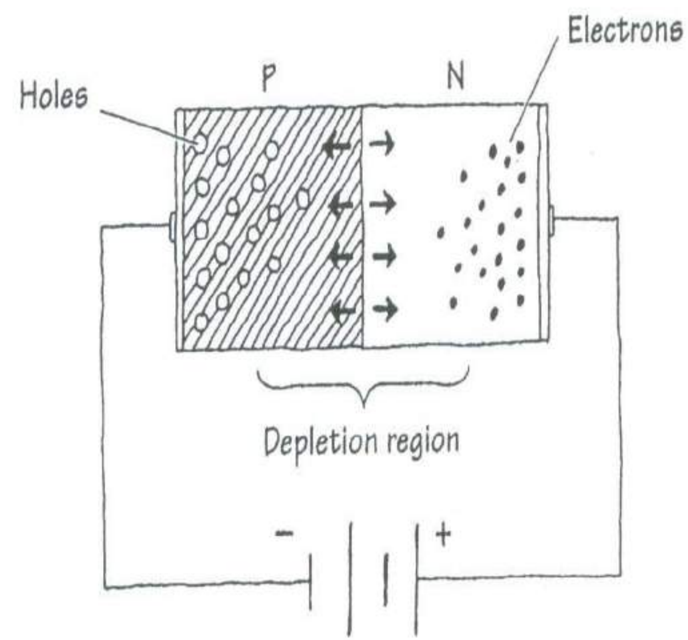
# pn-junction

- Applying an external voltage to overcome the potential barrier is called forward biasing, as shown in the figure.
- Electrons from the n-side and holes from the p-side are forced toward the centre by the electrical field supplied by the battery.
- As a result, depletion region gradually diminishes allowing flow of charges to and from either sides.



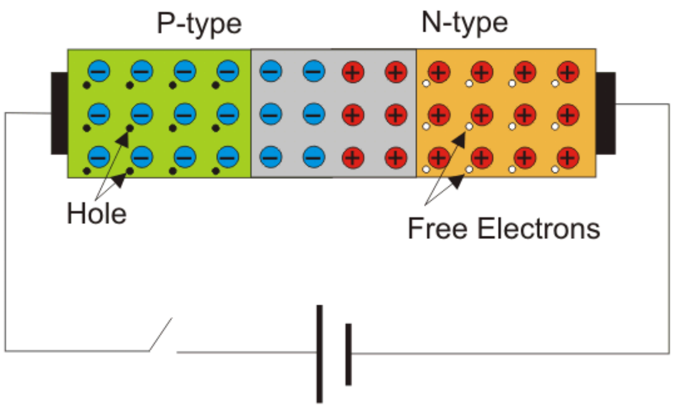
# pn-junction

- Application of an external voltage that enhances the potential barrier is called reverse biasing, as shown in the figure.
- In the figure, holes in the p-side are forced to the left while electrons in the n-side are forced to the right.
- This results in an increased depletion region.



# pn-junction

- For Si, barrier potential = 0.7 V
- For $0 \leq V_i < 0.7$ V, depletion layer and potential barrier diminishes; but still no current.
- For $0.7 \text{ V} \leq V_i$, depletion layer and potential barrier vanishes; current flows across the junction.
- For $V_i < 0$ V, depletion layer and potential barrier increases; no current.



# pn-junction

- **Zener breakdown:** If doping level is very high, then the depletion layer will be very thin.  For large reverse voltage, high electric field appears across thin depletion layer. the covalent bonds may rupture giving large number of hole-electron pairs. The phenomenon was first observed and explained by Dr. Clarence Zener in 1934 and is thus named after him.

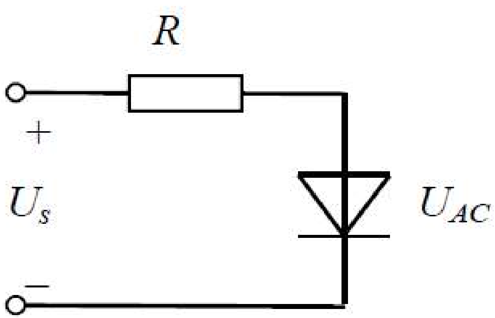
- **Avalanche breakdown:** For large reverse voltage, a thermally generated carrier may acquire very high energy and collide with crystal atoms to dislodge another valence electron; they in turn will dislodge another two valence electrons and so on.

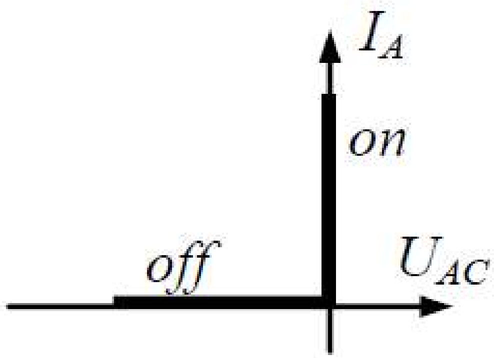
# Diode

- A diode is a 2-lead semiconductor that acts as a one way gate to electron flow – Diode allows current to pass in only one direction.
- In a forward-biased diode current is allowed to flow through the device.
- In a reverse-biased diode current is blocked.

# Diode characteristic

- The I-V characteristic (voltage vs current) of an ideal diode is as follows:

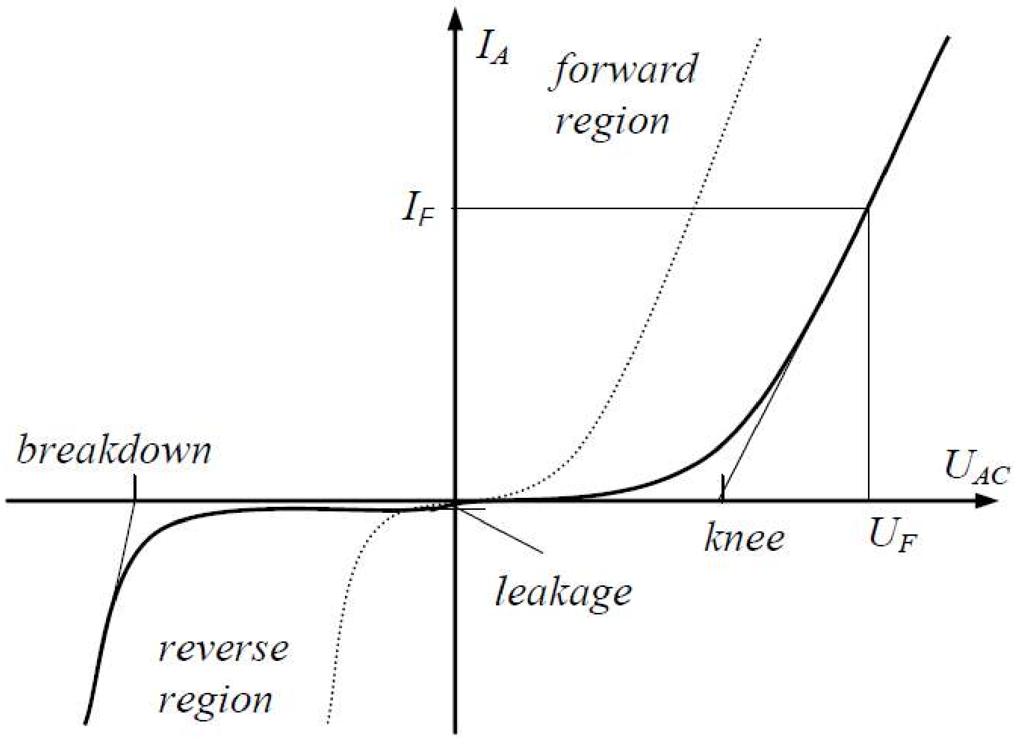



- However, practical diodes require some cutin voltage to conduct; otherwise, the diode will not conduct.
- This cutin voltage is reqd. to overcome the potential barrier.
- Typically for silicon diodes, this cutin voltage is 0.7 volt and for germanium diode is 0.3 volt.

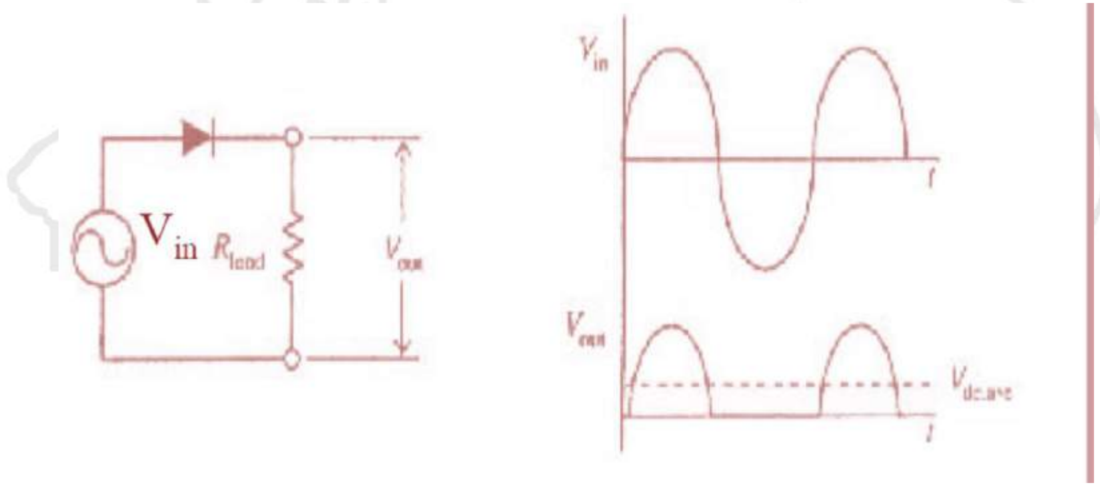
# Diode characteristic

- In reverse bias, leakage current due to thermally generated hole-electron pair.
- I-V characteristic of a practical diode is as follows:



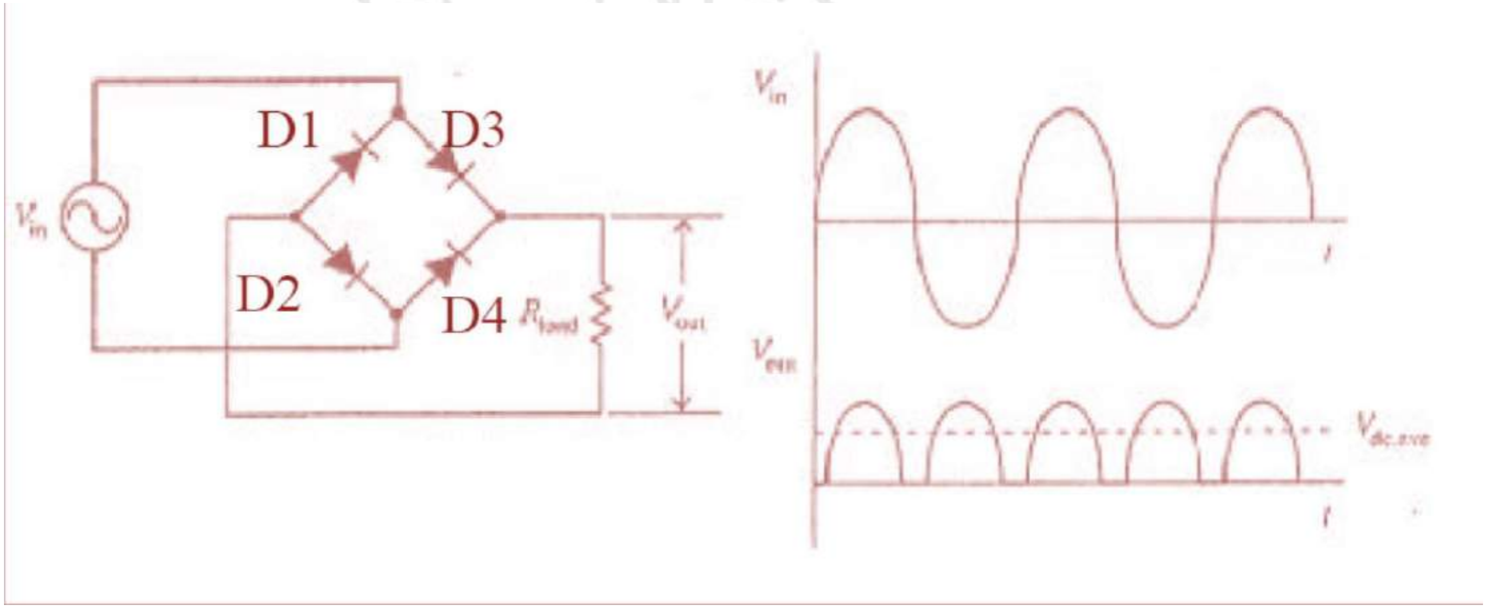
# Diode applications: ac to dc

- Converts ac input voltage to a pulsed dc output voltage.
- **Half-wave rectification:** When the ac input is negative at diode's anode, the diode blocks current → $V_{out} = 0$.
- Diode introduces a 0.6V drop so o/p peak is 0.6V smaller than the i/p peak.
- The o/p frequency is same as the i/p frequency.

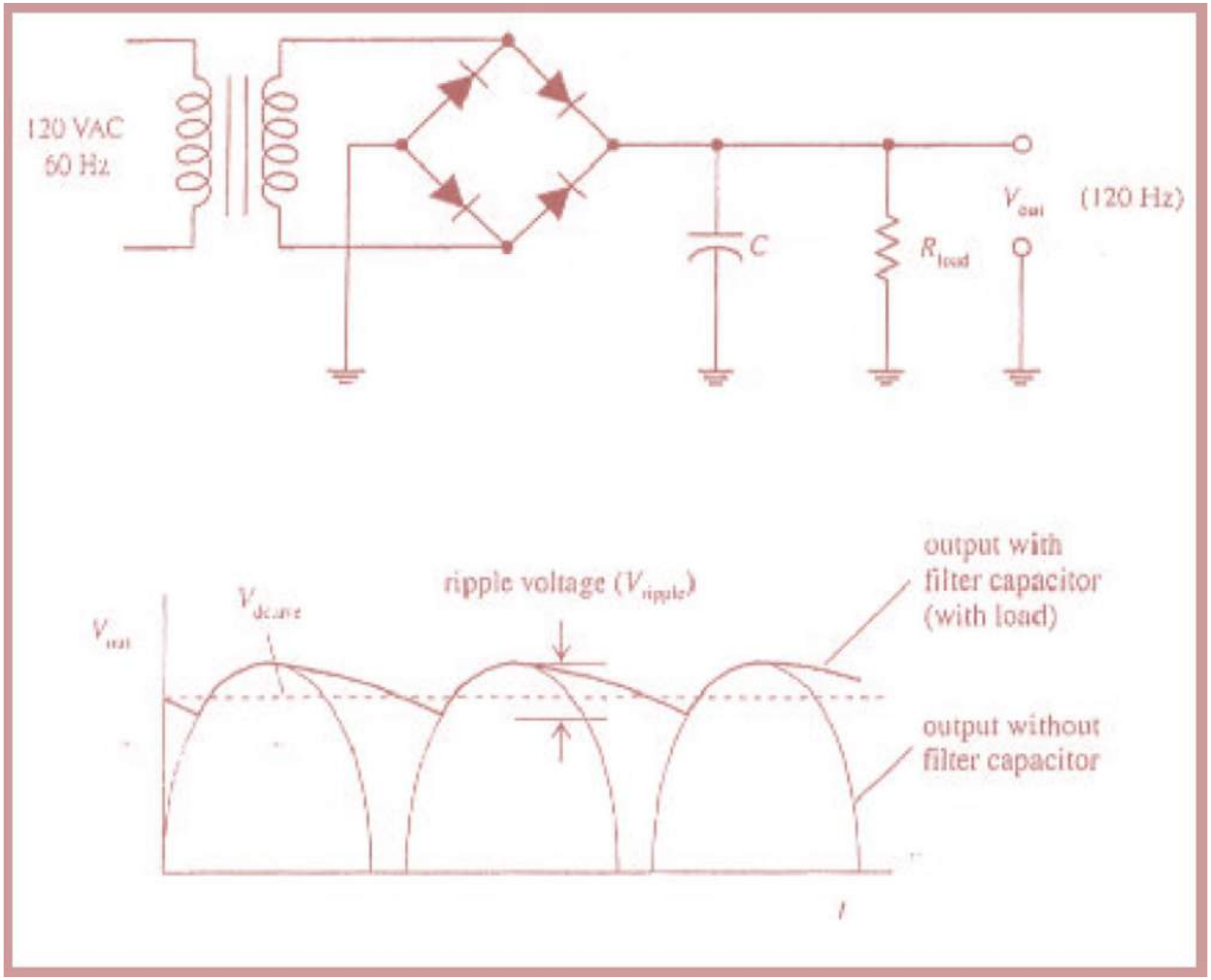


# Diode applications: ac to dc

- A **full-wave rectifier** does not block negative swings in the i/p, rather it transforms them into positive swings at the o/p.
- o/p voltage peak is 1.2V below the i/p voltage peak.
- The o/p frequency is twice the i/p frequency.

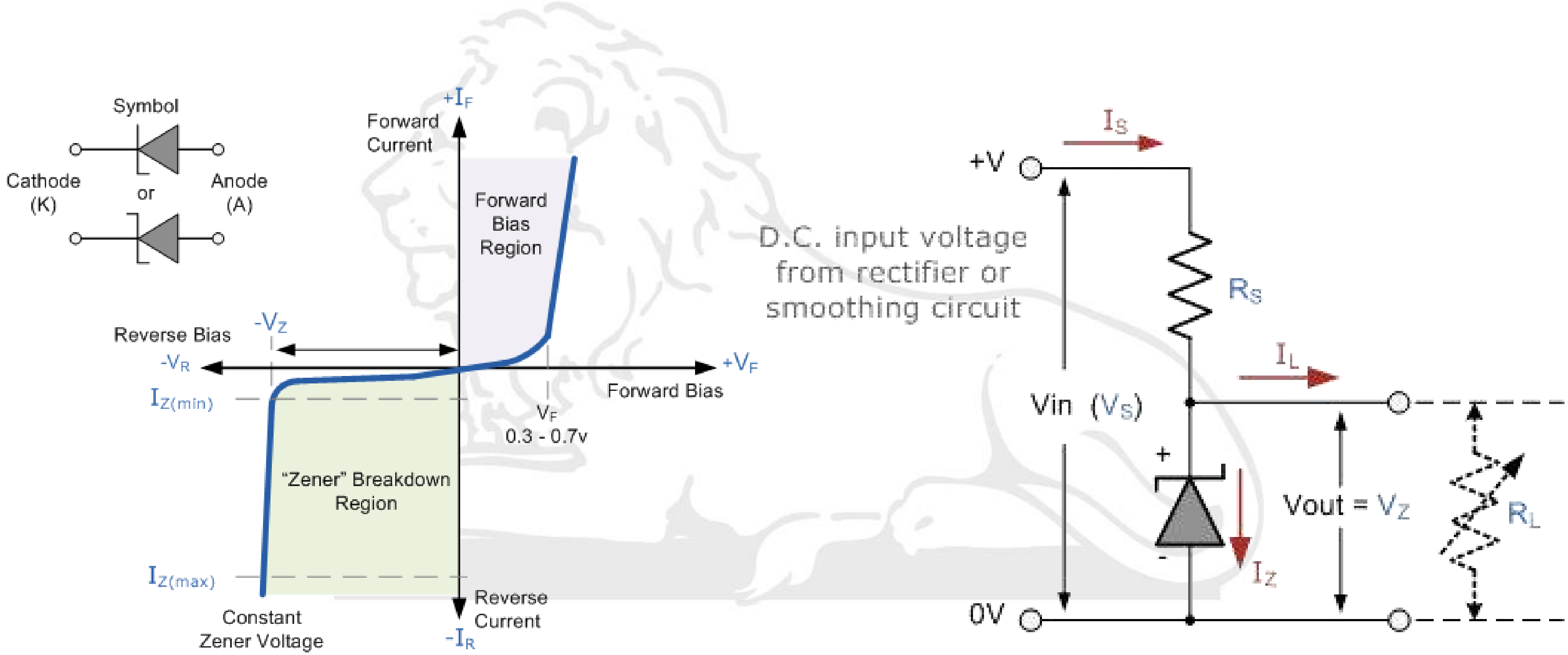


# Diode applications: ac to dc



# Diode applications: voltage regulation

- **Zener Diodes** can be used to produce a stabilized voltage output with low ripple under varying load current conditions.

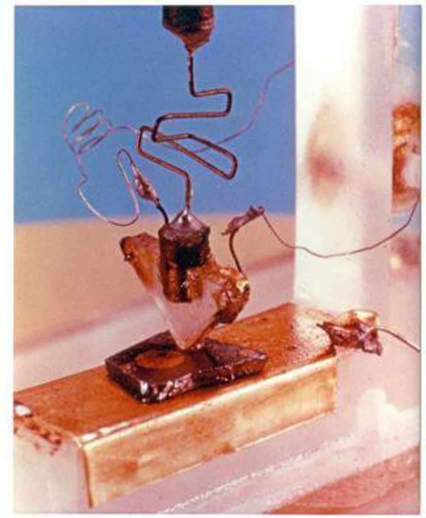


# Transistor

- Guglielmo Marconi invents radio in 1895; but, for long distance travel, signal must be amplified.

- Lee De Forest improves on Fleming's original vacuum tube to amplify signals by making use of third electrode; but, too bulky for most applications.

- Bardeen, Brattain, and Shockley invented a current transistors made of doped silicon at Bell Labs in the year 1947.



# Transistor

- *"The Transistor was probably the most important invention of the 20th Century*…"

  – The American Institute of Physics

- Conferred the Nobel Prize in physics in the year 1956

# Transistor

- The word "transistor" was coined to describe the operation of a "transfer resistance".

- First, a point-contact transistor was produced that included two diodes placed very closely together such that the current in either diode had an important effect upon the current in the other diode.

- By proper biasing the diodes, it was possible to obtain power amplification of electric signals between the diode common layer and other layers.

# Transistor

- The point-contact transistor had certain drawbacks:
  - high sensitivity to temperature,
  - production problems → difficulty to reproduce the same electrical qualities in close tolerance for mass production
  - low amplification, especially at high frequencies.
- A more mechanically and electrically stable device was constructed by forming junctions rather than point contacts.
- General classes of transistors used in electronics today are:
  - **B**ipolar **J**unction **T**ransistor (BJT)
  - **J**unction **F**ield-**E**ffect **T**ransistor (JFET)
  - **M**etal-**O**xide **S**emiconductor **FET** (MOSFET)

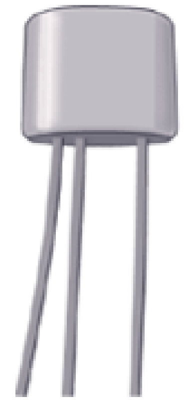
# Bi-polar Junction Transistor (BJT)

- The Bi-polar junction transistor (BJT) is a three-terminal device with **emitter**, **base** and **collector** terminals.

- Made of three adjacent regions of doped semiconductor.

- Both electrons and holes participate in the conduction process in bipolar devices.

- Acts as:
  - – an electrically controlled switch
  - – a current amplifier.

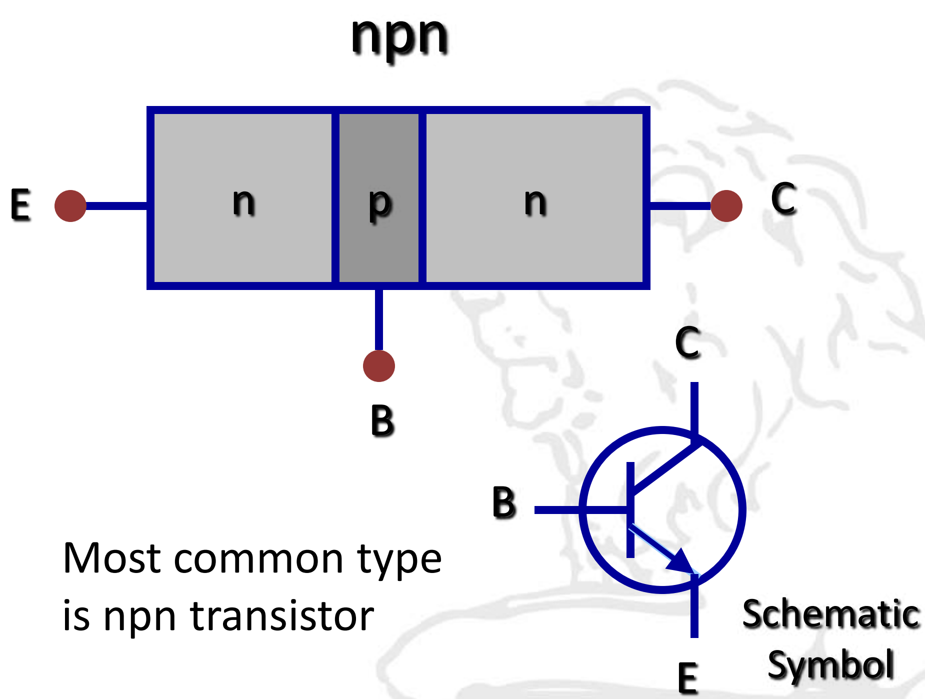


Metal can package

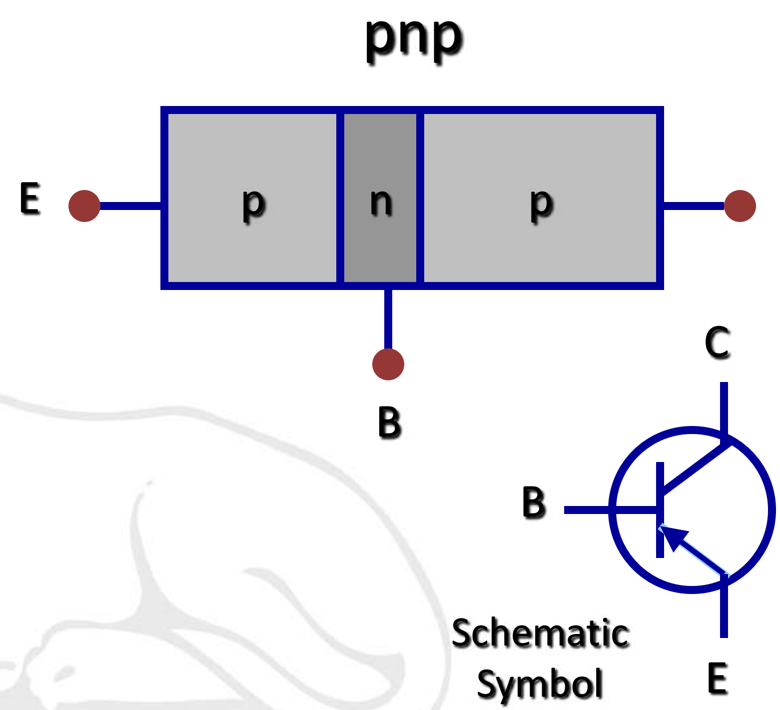

Plastic case package

# BJT types

- From the physical structure, two types of BJT: ***npn*** and ***pnp***



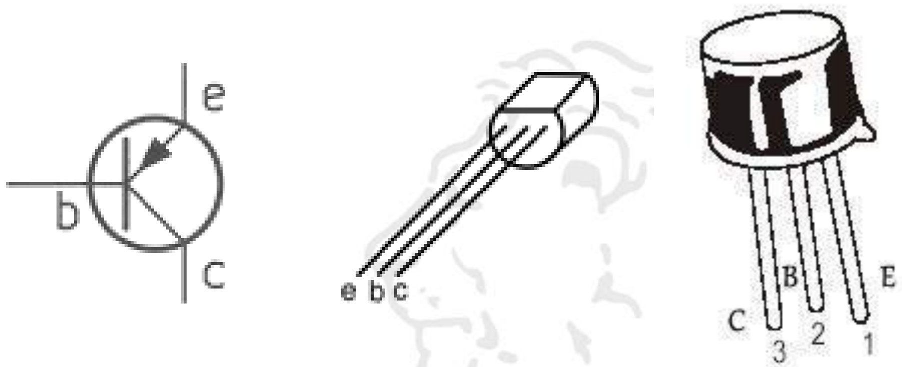

Most common type is npn transistor



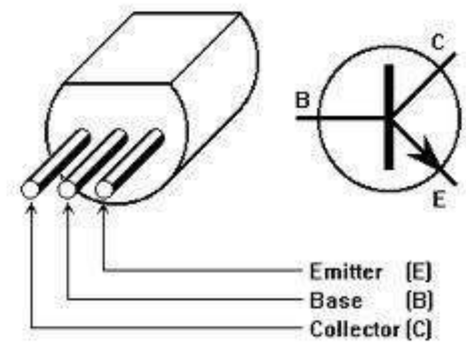

- Collector doping is usually ~ $10^6$
- Base doping is slightly higher ~ $10^7 – 10^8$
- Emitter doping is much higher ~ $10^{15}$

# Identifying BJT terminals and types

- How do you identify the BJT pins (terminals)?




npn transistor

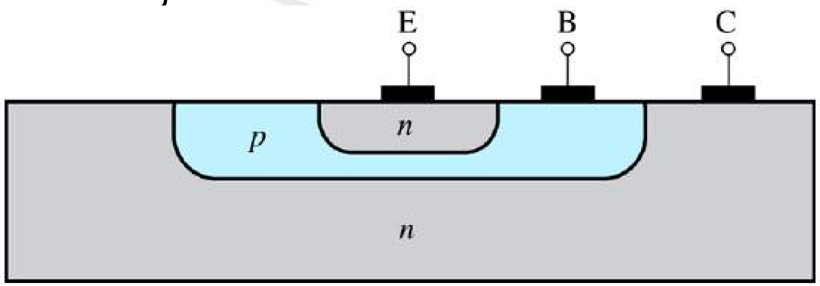



pnp transistor – configuration just opposite to that of npn

- How do you identify transistor type – npn or pnp type?
  - Do resistance check with a multimeter across the E-B and the C-B terminals.

# Structure of BJT

- In npn transistor, one thin layer of p-type, sandwiched between two layers of n-type.
- In pnp transistor, one thin layer of n-type, sandwiched between two layers of p-type.
- Similar to two back-to-back connected diodes. The emitter and the base form one of the diodes, while the collector and the base form the other diode.



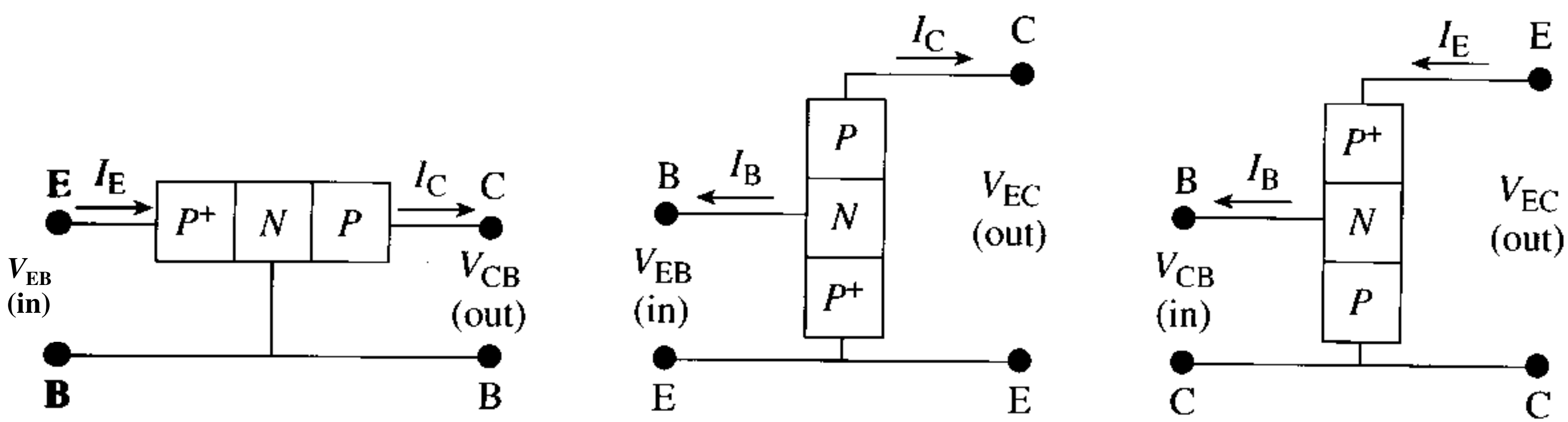

- Generally,
  - Base very thin
  - Collector size > Emitter size
  - Emitter highly doped >> Base doping

# BJT operating modes

- BJT can operate in three different modes depending on the junction bias.
- **Active mode:** E-B forward-biased, C-B reverse-biased
  - most important mode → central to amplifier operation
- **Saturation mode:** Both junctions forward-biased
  - Junction barrier potentials cancel each other causing a virtual short
- **Cut-off mode:** Both junctions reverse-biased
  - Currents in the transistor reduce to zero.
- Switching applications utilize both the cut-off and saturation modes → basis for digital logic circuits.

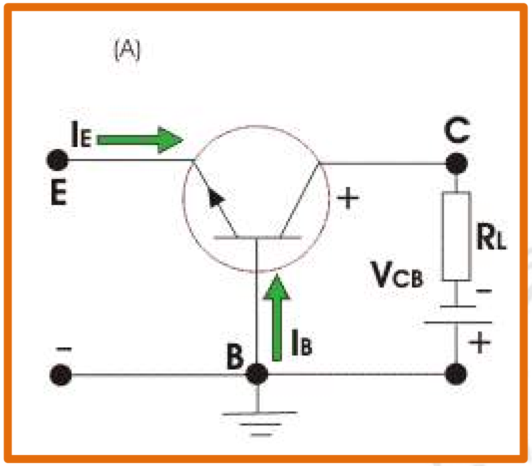
# Configurations of BJT connections

- Three basic configurations based on which of the 3 terminals is common to both input and output circuits:
  - common base (CB) connection
  - common emitter (CE) connection,
  - common collector (CC) connection.

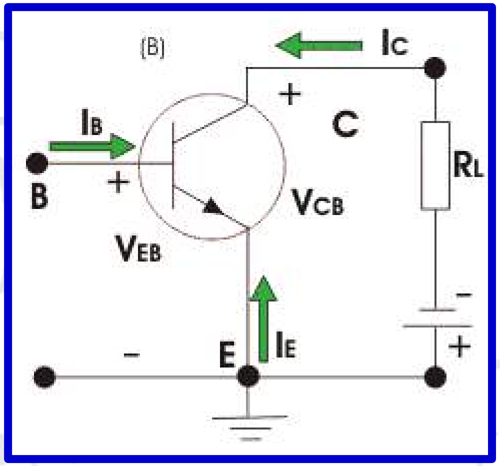



(a) Common base (b) Common emitter (c) Common collector

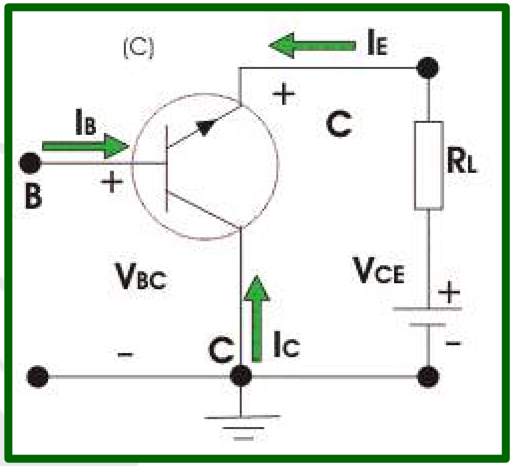
# Configurations of BJT connections




Common-Base
Configuration



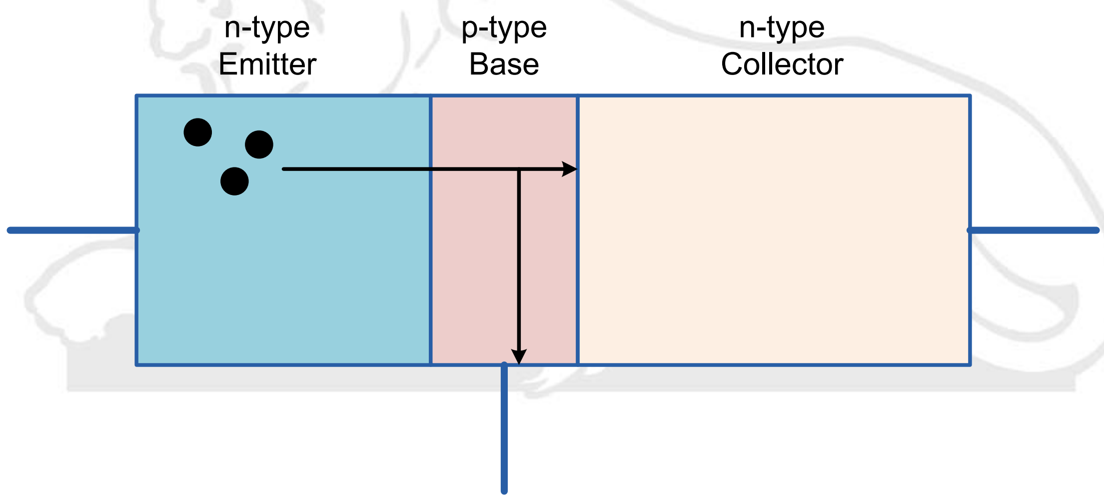

Common-Emitter
Configuration




Common-Collector
Configuration

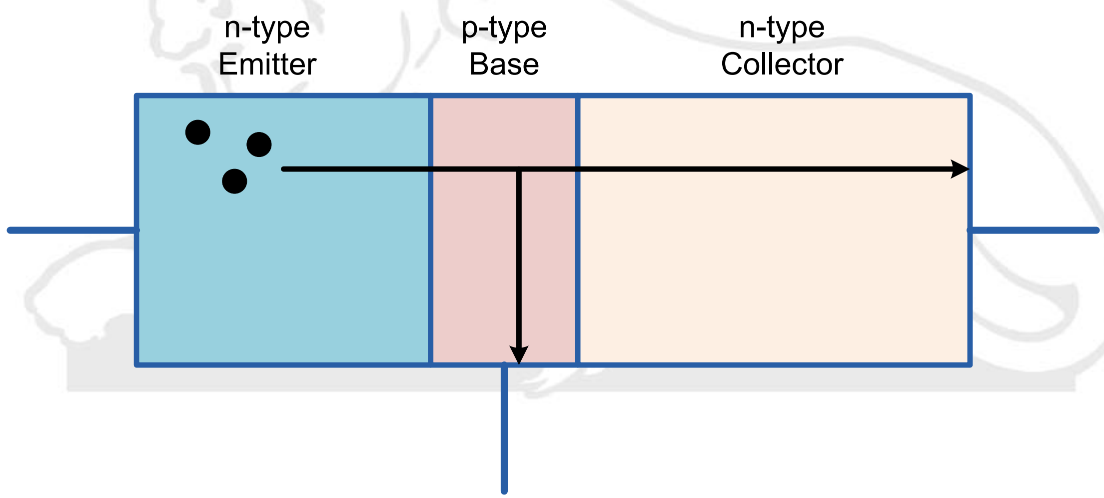
# BJT current components

- Considering an npn transistor in active mode, electrons in emitter regions are injected into base due to the forward bias at E-B junction.
- Since emitter is highly doped and base is narrow, the base gets flooded with electrons; only a small fraction of it can drift out through the base terminal.



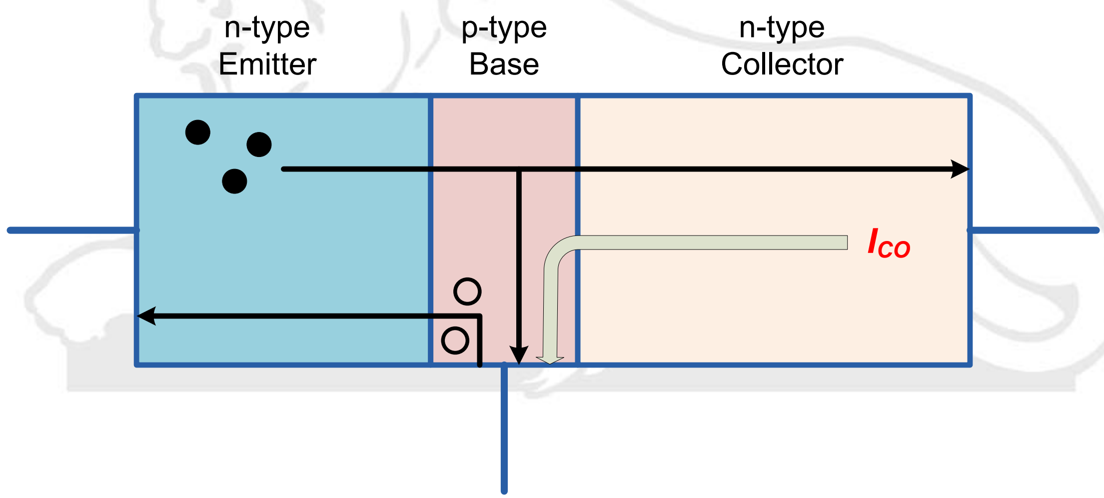
# BJT current components

- Most of the injected electrons (say $\alpha$ times of the total) reach the edge of C-B junction.
- Due to the reverse bias at C-B junction, these electrons gain enough momentum to cross the base and swept into the collector; and eventually drifted out of the collector terminal.



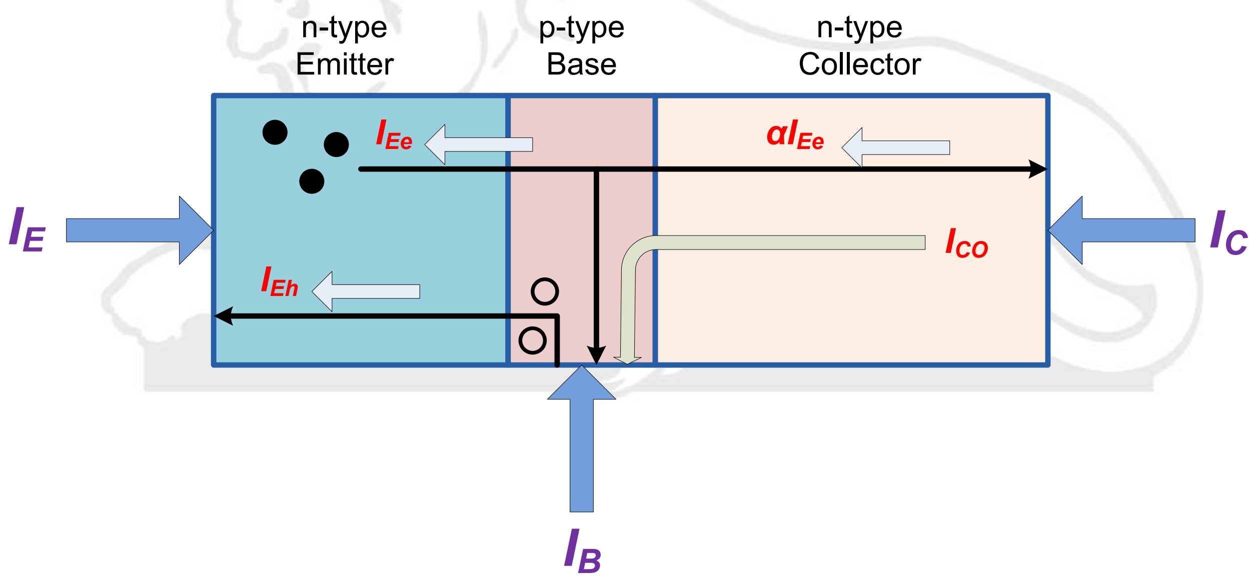
# BJT current components

- The holes in the base region will flow across the forward-biased E-B junction and drift out of the emitter terminal; but no flow of hole across the reverse-biased C-B junction.
- There will also be the usual reverse saturation current $I_{CO}$ across the reverse-biased C-B junction.



# BJT current components

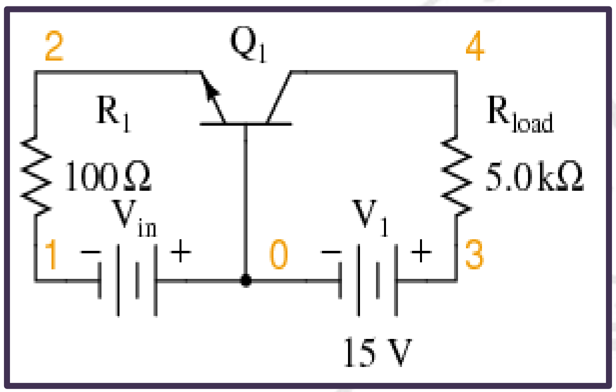
- So we get, emitter current $I_E = -[\,I_{Ee} + I_{Eh}\,]$.
- Collector current $I_C = \alpha I_{Ee} + I_{CO}$.
- Base current $I_B = I_{Eh} + (1 - \alpha)I_{Ee} - I_{CO}$.
- Check that $I_E + I_C + I_B = \mathbf{0}$, conforming to KCL.

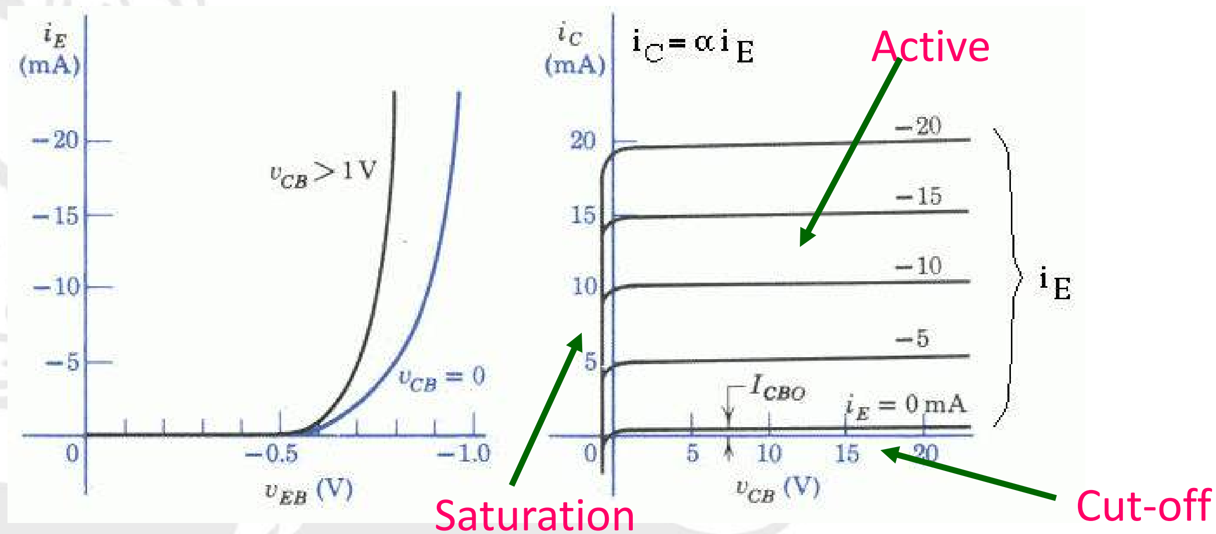


# CB characteristics of BJT

- Current gain: $\boxed{\dfrac{I_C}{-I_E} = \dfrac{\alpha I_{Ee} + I_{CO}}{I_{Ee} + I_{Eh}} \approx \dfrac{\alpha I_{Ee}}{I_{Ee}} = \alpha \approx 1}$

- Hence called alpha gain (dc alpha gain)



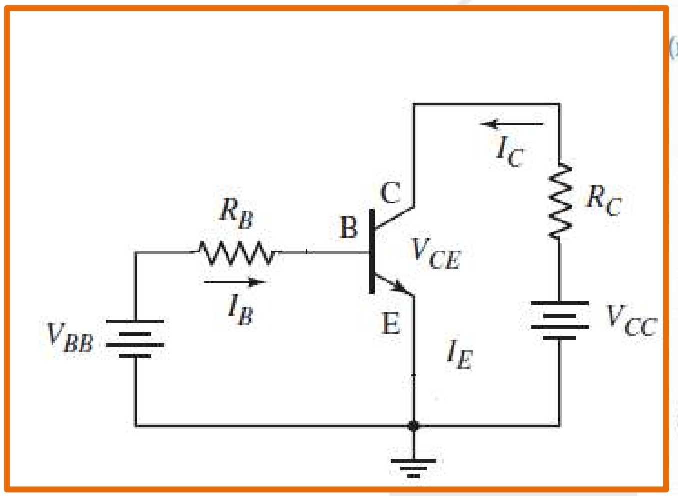

Input or Emitter Characteristic

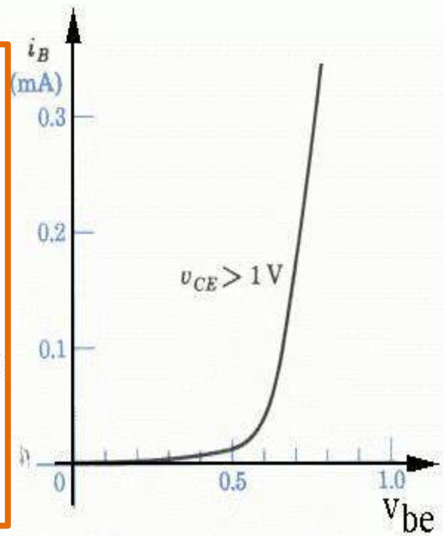
Output or Collector Characteristic

# CE characteristics of BJT

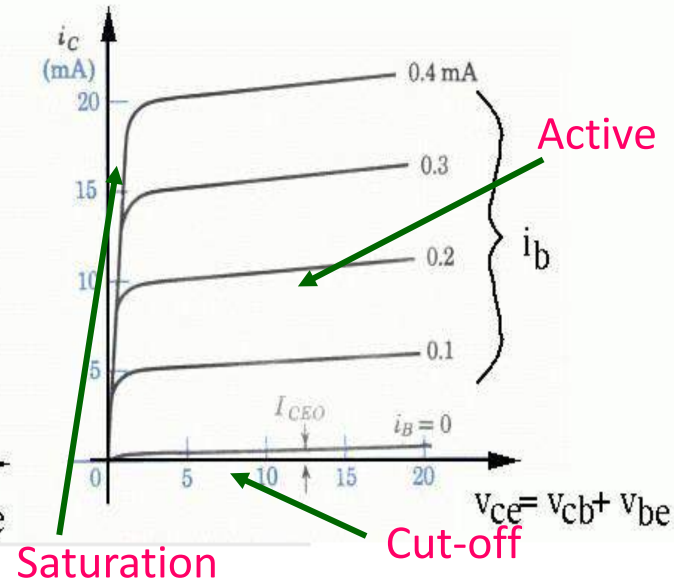
- Current gain: $\boxed{\frac{I_C}{I_B} = \frac{\alpha I_{Ee} + I_{CO}}{I_{Eh} + (1-\alpha) I_{Ee} - I_{CO}} \approx \frac{\alpha I_{Ee}}{(1-\alpha) I_{Ee}} = \beta}$

- Called beta gain (dc beta gain) which is generally very high.



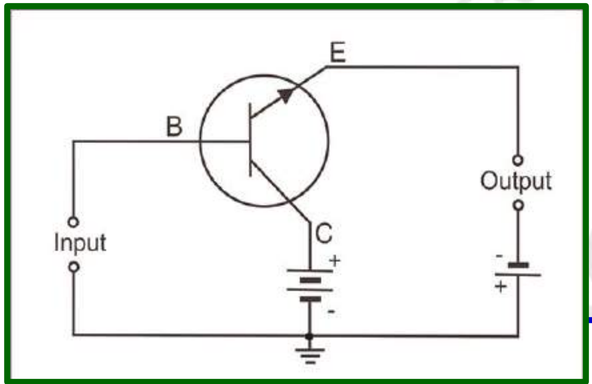

Input or Base Characteristic

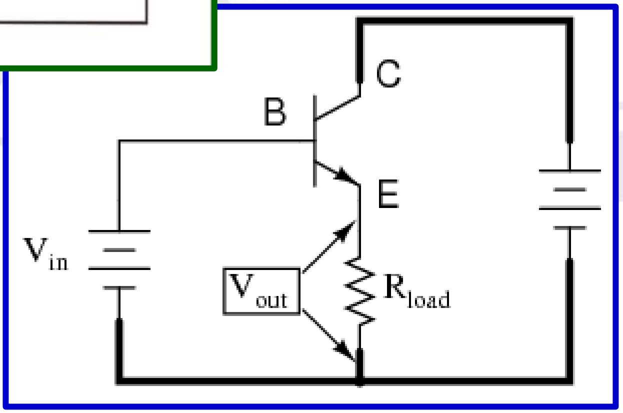


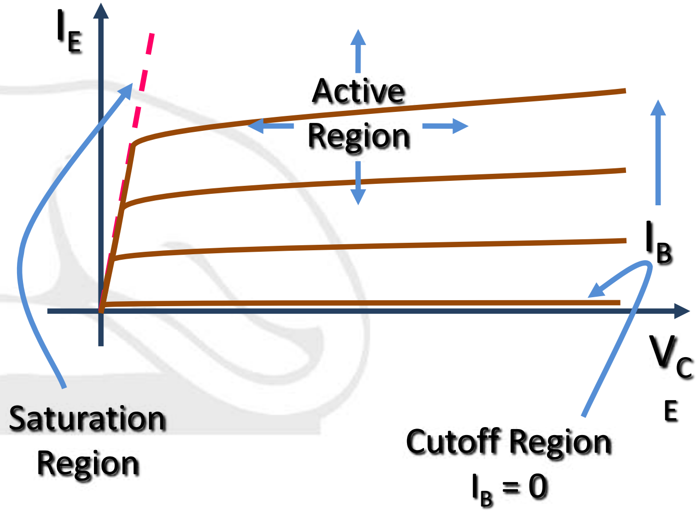

Output or Collector Characteristic

# CC characteristics of BJT

- The CC-biasing circuit is basically equivalent to CE-biased circuit but with load in the emitter terminal and so instead of looking at $I_C$ as a function of $V_{CE}$ and $I_B$ we look at $I_E$.
- Also, since $\alpha \sim 1$, and $\alpha = I_C / I_E$ , we have that $I_C \sim I_E$

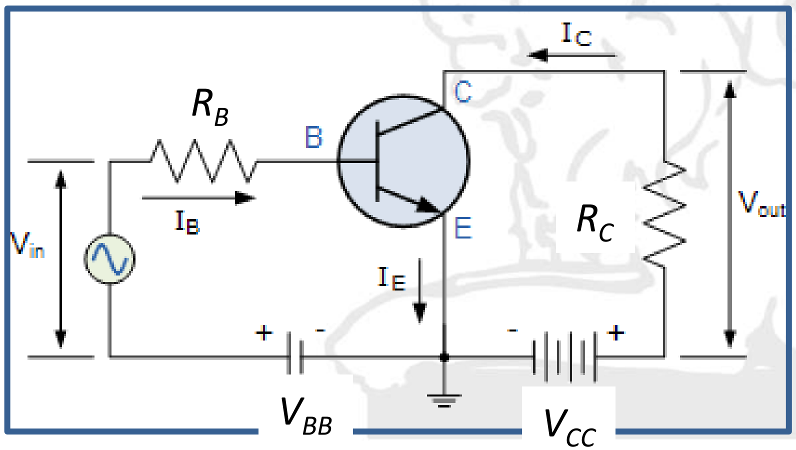


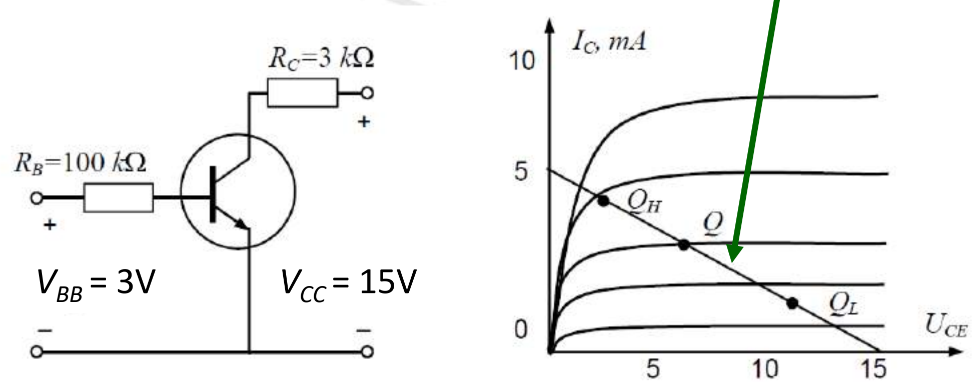



# BJT as an amplifier

- CE configuration; Active mode; significant current gain
- Biasing the transistor: applying voltage to get the transistor to achieve certain operating conditions → establishing suitable operating point or quiescent-point (Q-point).

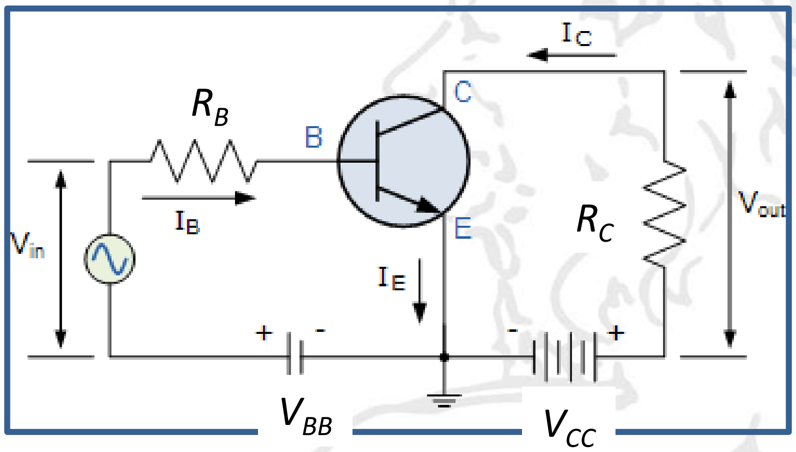



Load Line: $I_C = -\frac{1}{R_C}V_{CE} + \frac{V_{CC}}{R_C}$



# BJT as an amplifier

- As the input ac voltage swings, output voltage swings about the Q-point with opposite polarity.
- Output = voltage at the collector terminal ($V_{CE}$) or voltage across the load ($V_{out}$)




$$V_{CE} = V_{CC} - I_C R_C = V_{CC} - \beta I_B R_C$$

$$= V_{CC} - \beta \frac{V_{BB} + V_{in} - V_{BE}}{R_B} R_C$$

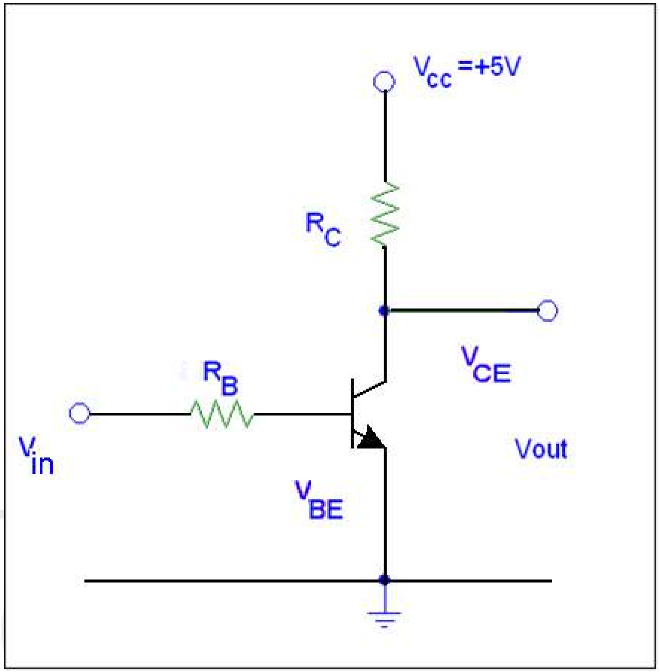
$$= V_{CC} - \beta \frac{V_{BB} - V_{BE}}{R_B} R_C - \beta \frac{V_{in}}{R_B} R_C$$

$$V_{out} = -I_C R_C = V_{CE} - V_{CC} = -\beta \frac{V_{BB} - V_{BE}}{R_B} R_C - \beta \frac{V_{in}}{R_B} R_C$$

- The dc component in the output is removed by using a dc blocking capacitor.

# BJT as a switch

- At cut-off
  - Input voltage $V_{in} < 0.7$ V (LOW)
  - No current flows; $I_C = 0$
  - $V_{out} = V_{CE} = V_{CC}$ (HIGH)
  - Acts as an open switch




- At saturation
  - Input voltage $V_{in} > 0.7$ V (HIGH)
  - $V_{out} = V_{CE} = V_{CB} - V_{EB} \sim 0.2$ V (LOW)
  - $I_C = (V_{CC} - V_{CE}) / R_C \neq \beta I_B$; operating pt. is set accordingly
  - Acts as a closed switch

# Field Effect Transistor (FET)

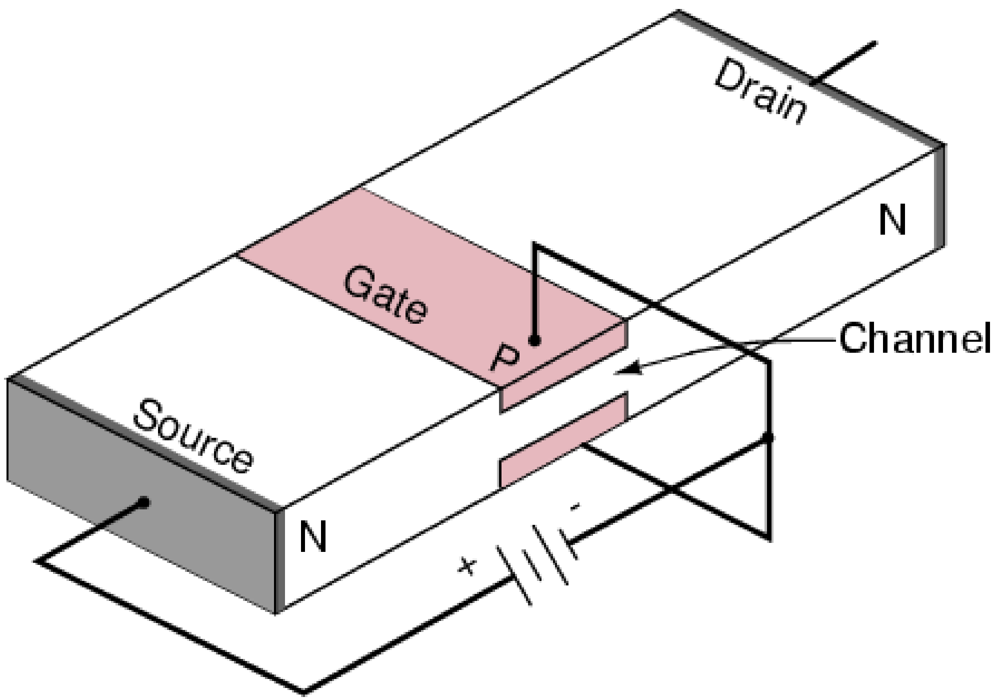
- The fundamental principle of FET was established by Lilienfield in 1925; the first working FET developed in 1955.
- The field-effect transistor (FET) is a generic term for a device that controls current through a circuit via an applied voltage, i.e. it behaves like a voltage-controlled resistor. (note that BJT is current-controlled device).
- FET has 3 terminals with current flowing through a channel:
  - **gate**: as in the “gate” keeper of the current
  - **source**: the terminal through which majority carrier enters the channel; source of the majority carrier.
  - **drain**: the terminal through which majority carrier leaves the channel; the destination of the current

# Field Effect Transistor (FET)

- Mainly three types of FETs
  - JFET (Junction Field-effect transistors)
  - MOSFET (metal-oxide-semiconductor FET)
  - MESFET (metal-semiconductor field-effect transistors)
- "**Unipolar**" – conduct either electrons or holes, not both
- Two Modes of FETs
  - Enhancement mode
  - Depletion mode
- The more used one is the n-channel enhancement mode MOSFET, also called NMOS

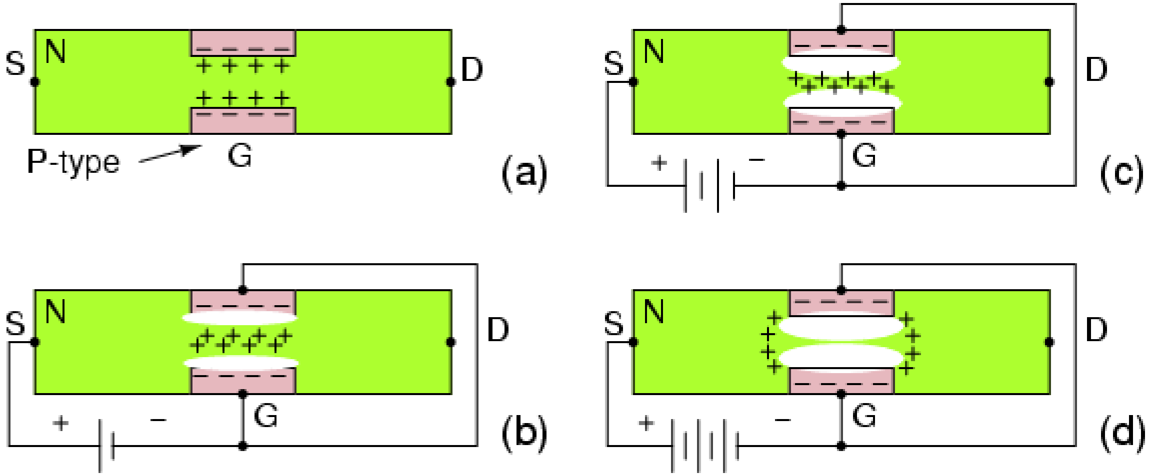
# Junction Field Effect Transistor (JFET)

- An n-channel JFET is composed of: n-type body, p-type gate
- Gate is generally reverse biased to control current flow.
- Channel conducts regardless of polarity between source and drain.



# Junction Field Effect Transistor (JFET)

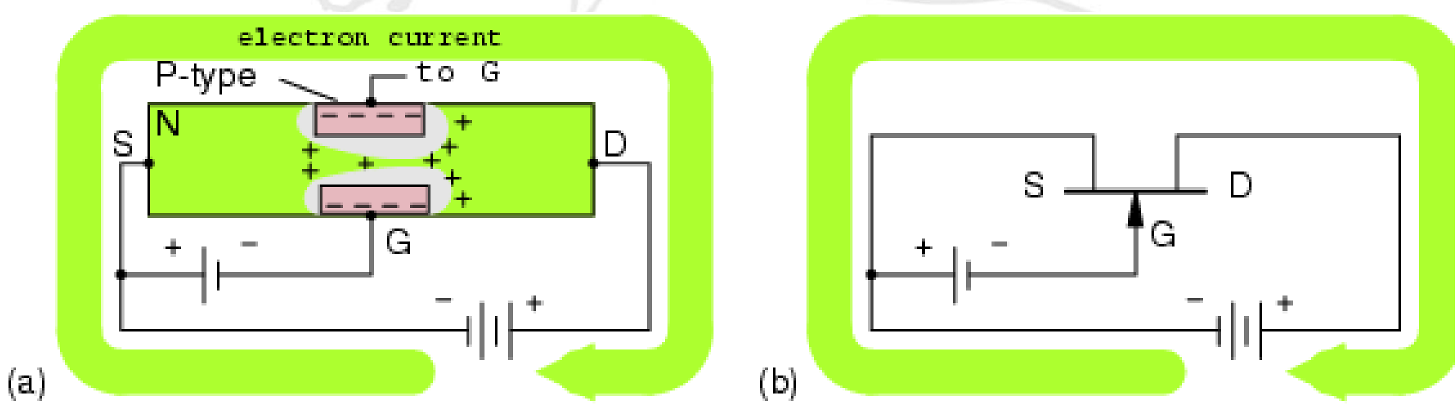
- The gate and channel form depletion regions; a stronger reverse bias makes the depletion regions wider and closer to each other.
- Thus, voltage controls channel resistance and hence the current from source to drain.




*(a) Depletion at gate diode.*
*(b) Reverse biased gate diode increases depletion region.*
*(c) Increasing reverse bias enlarges depletion region.*
*(d) Increasing reverse bias pinches-off the S-D channel.*

# Junction Field Effect Transistor (JFET)

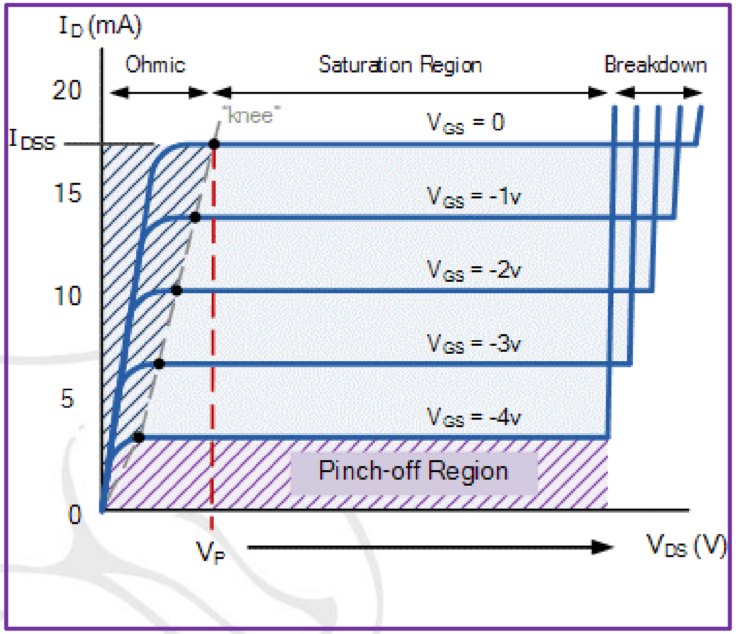
- Fig. (b) shows the schematic symbol for an n-channel FET. The gate arrow points in the same direction as a junction diode.
- In an n-channel JFET electrons flow from source to drain.
- Source and drain are interchangeable.



# JFET Characteristics

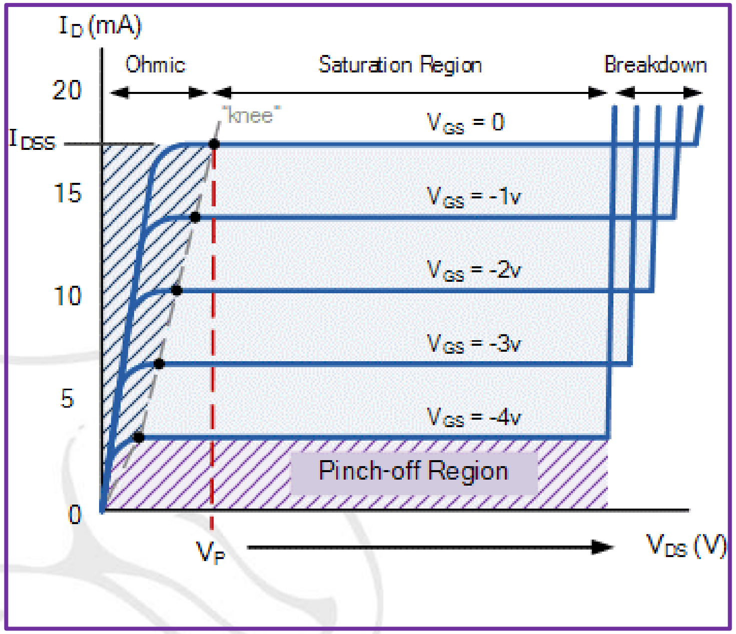
- **Ohmic region of operation:** At low drain-source voltages JFET behaves like a voltage-controlled variable resistance.

- **Saturation (active) region of operation:** At higher drain-source voltages (greater than the pinch-off voltage), it passes a constant current whose value depends on the applied gate-source voltage.



# JFET Characteristics

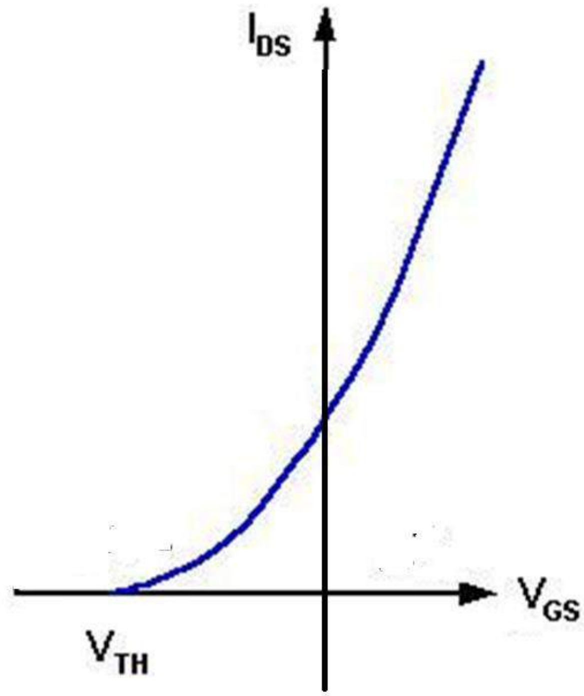
- Generally JFET is used in ‘saturation’ as a voltage controlled current source.
- For $V_{GS}$ = 0, pinch-off voltage = $V_p$ and saturation drain-current $I_{DS} = I_{DSS}$.
- As gate is more reverse-biased, pinch-off occurs for $V_{DS} < V_p$ and hence $I_{DS} < I_{DSS}$
- For $V_{GS} = -V_p$, pinch-off occurs even at $V_{DS} = 0 \rightarrow I_{DS} = 0$ (cut-off region)



# JFET Characteristics

- Thus, the threshold voltage $V_{TH} = -V_p$
- Dependency of the JFET current $I_{DS}$ on the applied gate voltage $V_{GS}$ (with a fixed $V_{DS} > V_p$) is given as

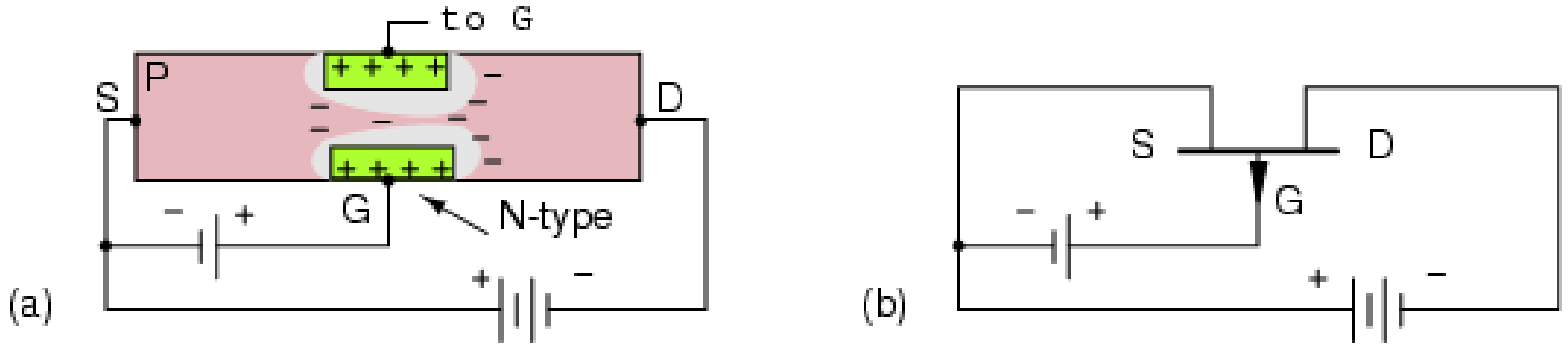
$$I_{DS} = I_{DSS}\left(1-\frac{V_{GS}}{V_{TH}}\right)^2$$




Transfer characteristic curve

# JFET Characteristics

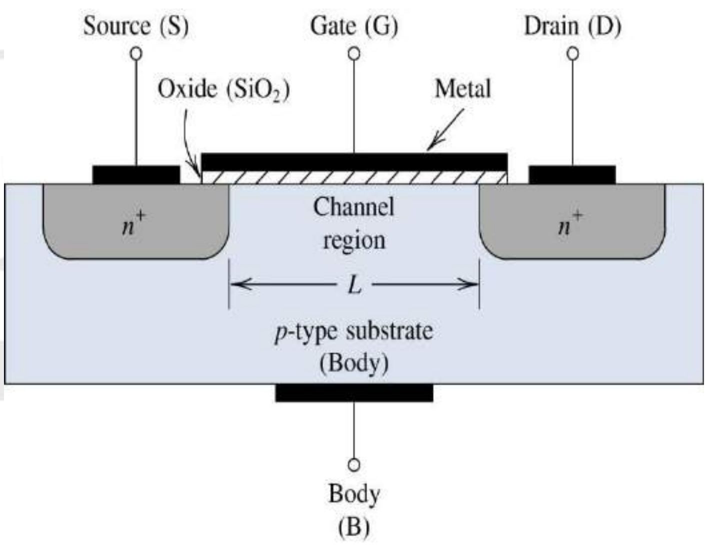
- A p-channel JFET is similar to the n-channel version, except with polarities reversed. Note that the arrow points out of the gate of the schematic symbol.




- The JFET source, gate, and drain correspond to the bipolar junction transistor's emitter, base, and collector, respectively.

# MOSFET – Enhancement type

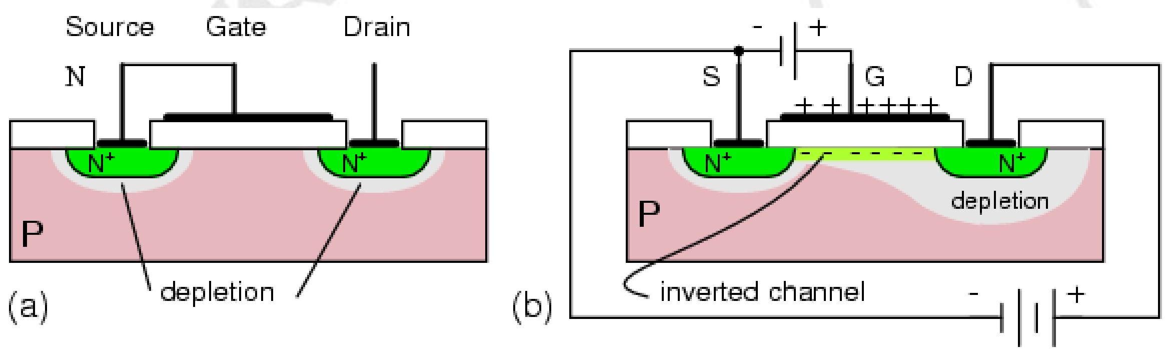
- A MOSFET is a FET with an insulated gate – while the MOSFET has source, gate, and drain terminals like the JFET, its gate lead is not in direct contact with the silicon.
- Today, most transistors are MOSFETs in digital integrated circuits, due to its two main advantages over other types
  - greater density
  - simpler geometry, hence easier to make



(b)

# MOSFET – Enhancement type

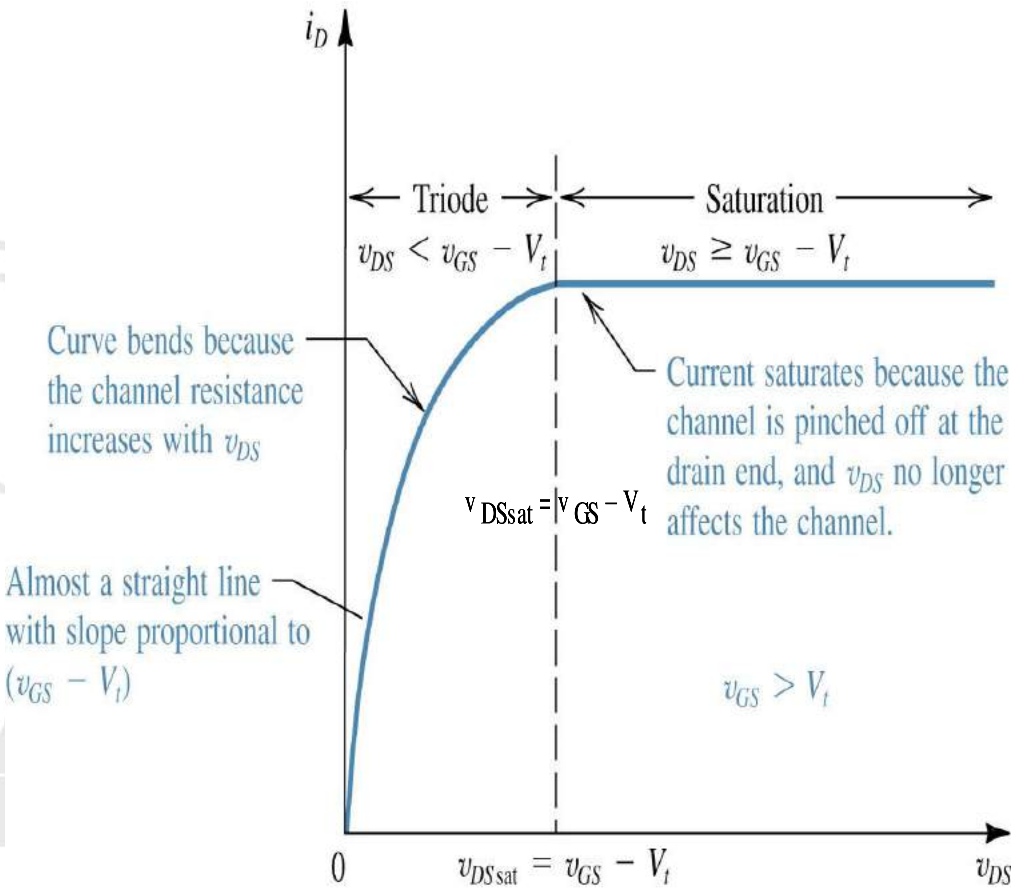
- A MOS capacitor exists between a pair of n-type diffusions in a p-type substrate.
- With no charge on the capacitor, the source and drain remain electrically isolated.
- A positive bias charges the capacitor and an inversion layer of electrons is formed in the p-type substrate below the gate oxide connecting source and drain.
- Thus, an n-type channel is created.



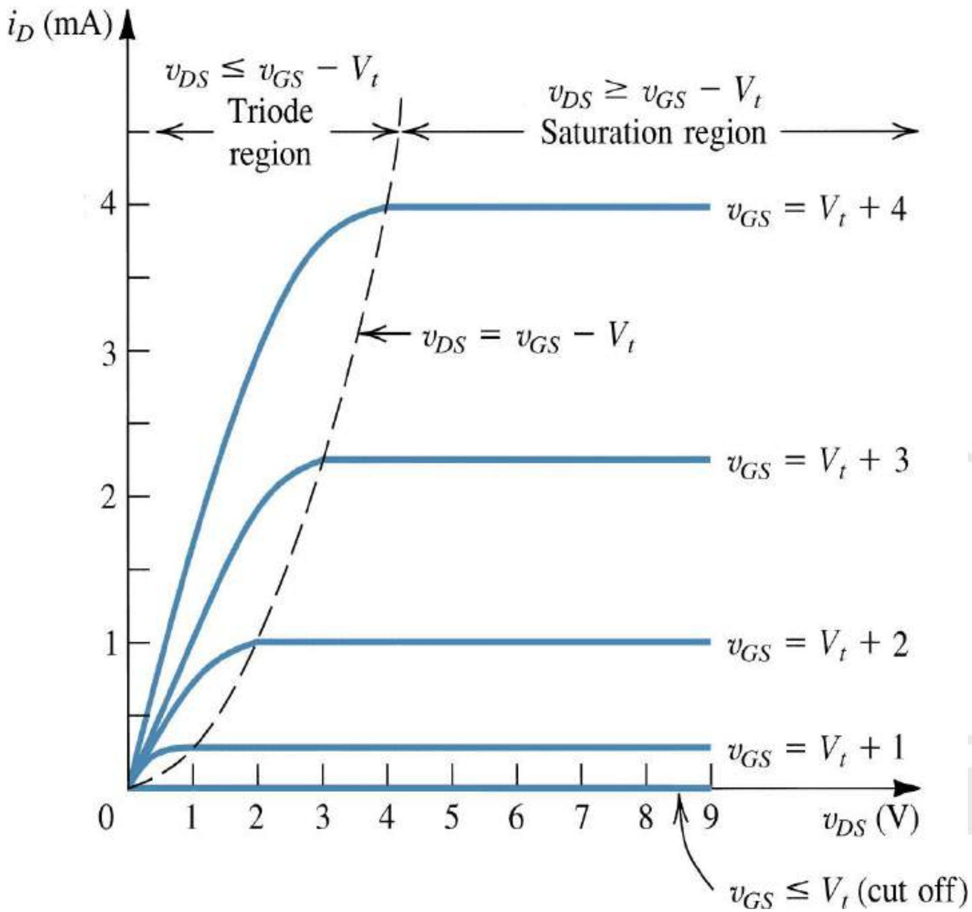

*N-channel MOSFET (enhancement type): (a) 0 V gate bias, (b) positive gate bias.*

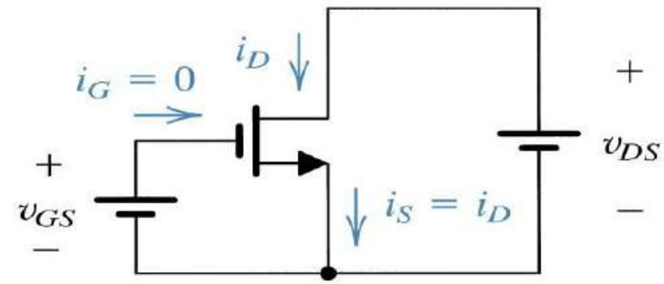
# MOSFET – Enhancement type

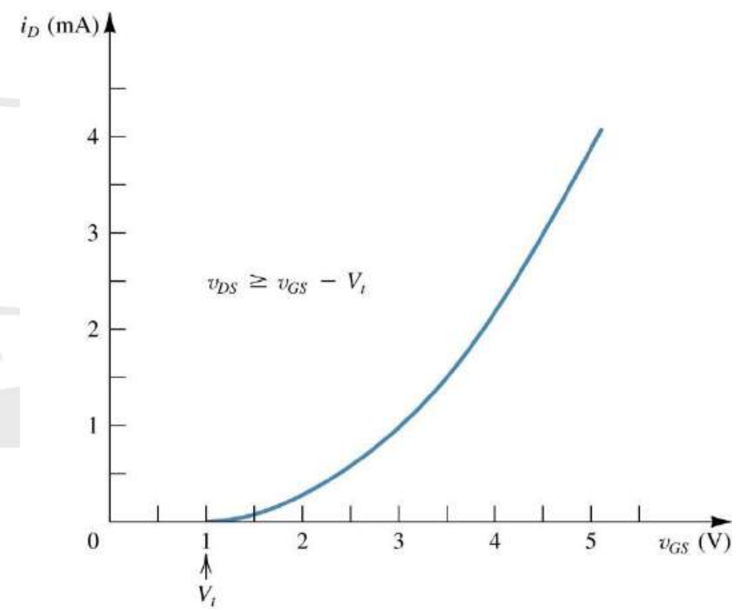
- Minimum $V_{GS}$ required to induce channel is the threshold voltage $V_t$.
- Increasing $V_{GS}$ above $V_t$ enhances the channel, hence it is called **enhancement type MOSFET**.
- Pinch-off occurs when $V_{GS} - V_{DS} = V_t$.



# MOSFET – Enhancement type



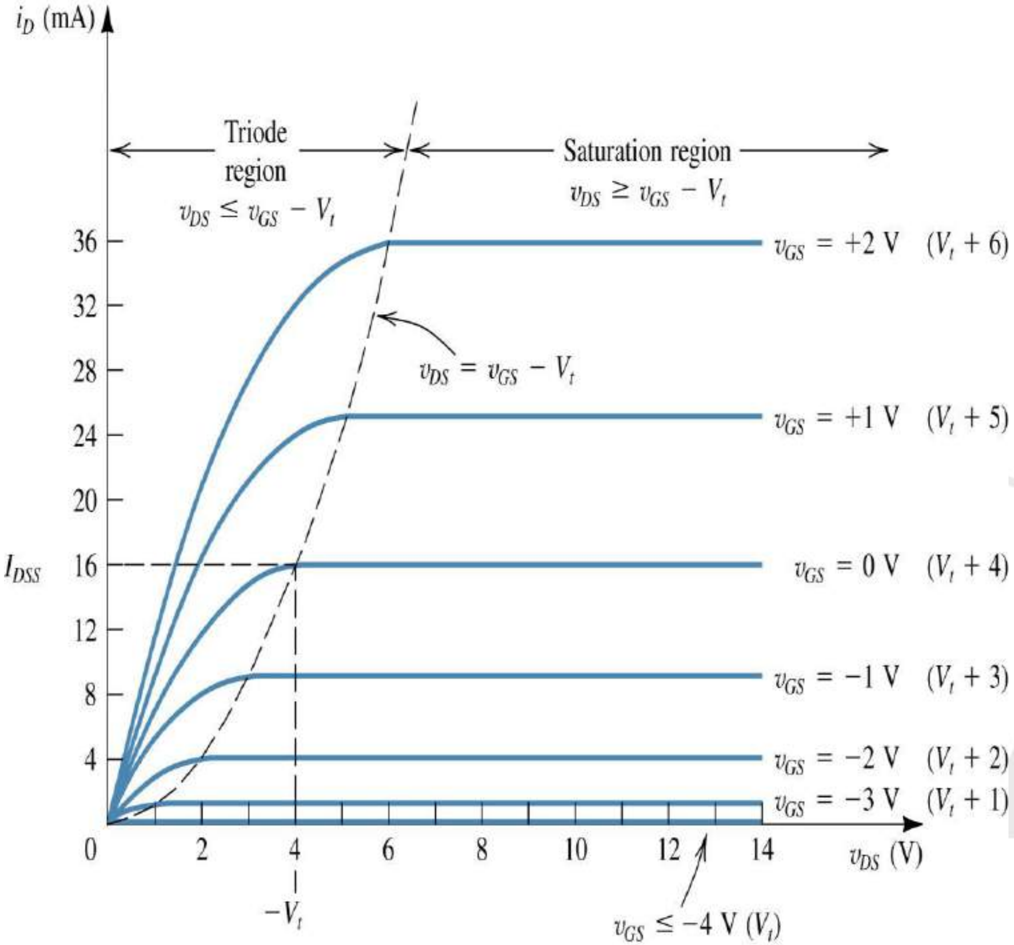



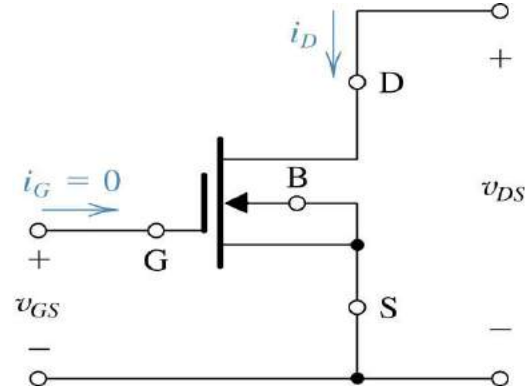



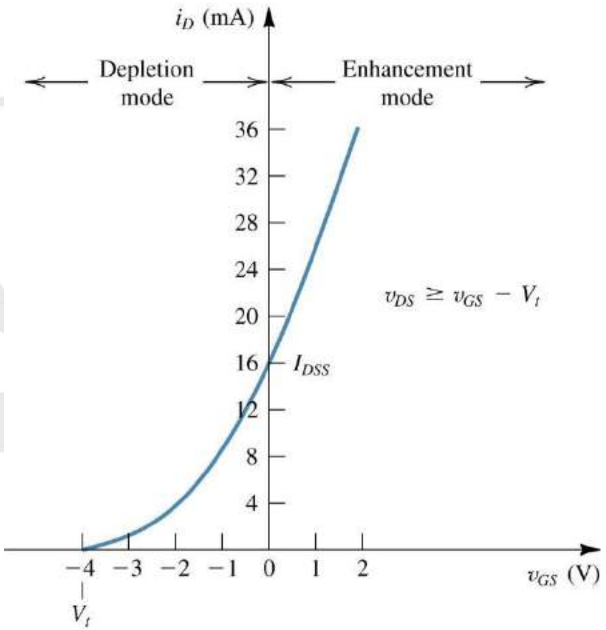
# MOSFET – Depletion type

- The depletion type MOSFET has similar structure to that the enhancement type MOSFET but with one important difference:
- The depletion MOSFET has a physically implanted channel.
- Thus an n-channel depletion-type MOSFET has an n-type silicone region connecting the source and drain at the top of the p-type substrate.
- Thus if a voltage $V_{DS}$ is applied, $I_D$ flows even for $V_{GS} = 0$.
- Applying a positive $V_{GS}$ enhances the channel by attracting more electrons. The reverse when applying negative volt. The negative voltage is said to deplete the channel (depletion mode).

# MOSFET – Depletion type



# MOSFET symbols