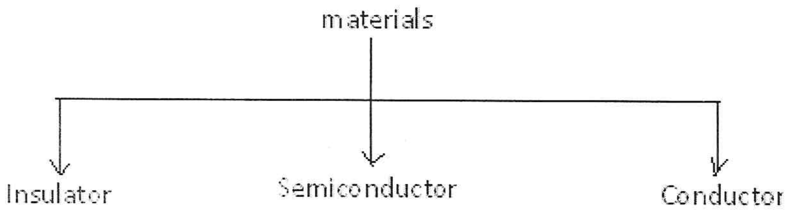
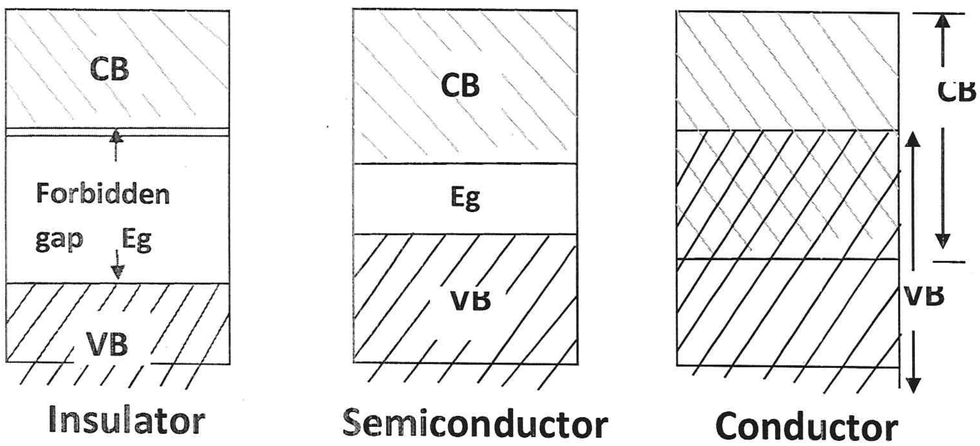
ELECTRONIC DEVICES & CIRCUITS



INSULATOR:

- Very low level (or negligible) of conductivity (Paper, Mica, glass, quartz)
- Typical resistivity level of an insulator is generally 10^{10} - 10^{12} Ω-cm
- A fill up Energy band between the valance band (VB) and conduction band (CB) is forbidden band gap
- The energy required for a valance electron to become a free electron: 1 eV = 1.6 x 10^{-19} J
- Large forbidden band gap is of the order greater than 3 EV



Energy band diagrams insulator, semiconductor and conductor

- Temperature/Applied electric field is insufficient to transfer electrons from VB to CB.

CONDUCTOR:

- High conductivity (Copper, Aluminum, Silver, Gold)
- Resistivity: 10^{-4} and 10^{-6} Ω-cm
- The Valance and conduction bands overlap
- Electron easily move from valance band to conduction band
- At room temperature when electric field is applied large current flows

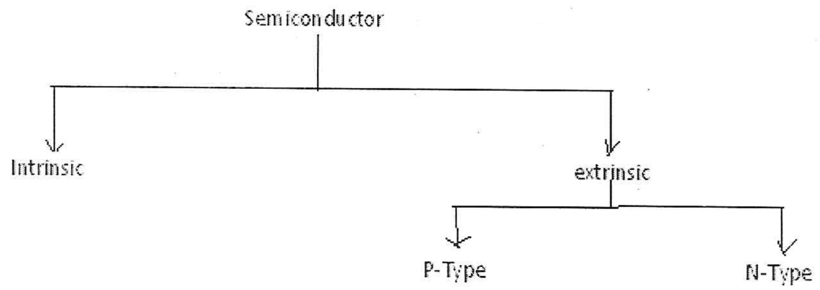
SEMICONDUCTOR:

- Conductivity between the insulator and conductor
- The resistivity level is in the range of 10 and 10^4 Ω-cm
- Commonly used are Silicon and germanium
- The forbidden band gap is of the order of 1Ev

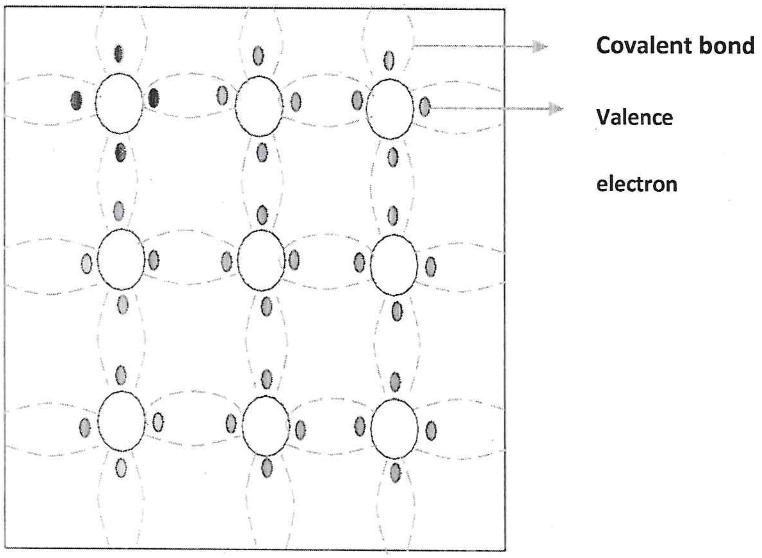
INSULATOR	SEMICONDUCTOR	CONDUCTOR
10^{12} Ω-cm (mica)	60 Ω-cm (Ge) 30 x 10^4 Ω-cm (Si)	1.68 x 10^{-8} Ω-cm (Copper)

Typical resistivity values

SEMICONDUCTOR CLASSIFICATION:

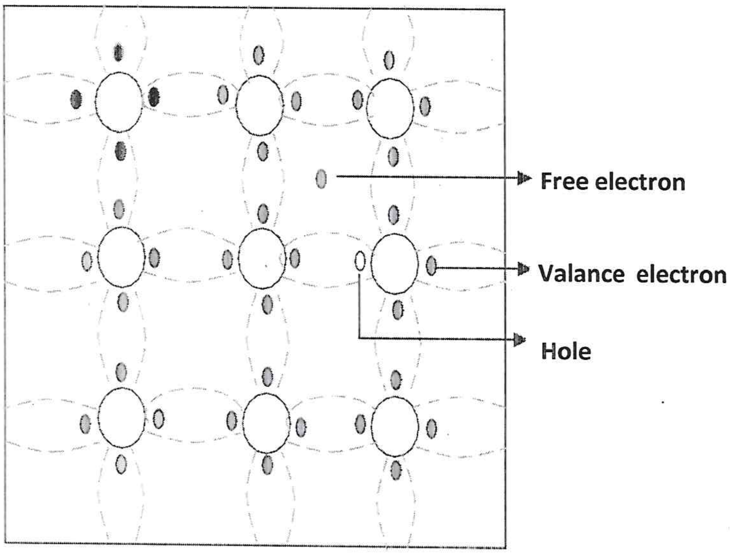


- A pure form of semiconductor is called as intrinsic semiconductor
- Conduction in intrinsic Semiconductor is either due to thermal excitation or crystal defects
- Si and Ge are the two most important semiconductors normally used
- Other examples, Gallium arsenide (GaAs), Indium Antimonide (InSb)



Crystal structure of Si at Room Temperature

- At room temperature few covalent bonds break up due to thermal energy
- The valance electrons that jump into conduction band are called as free electrons

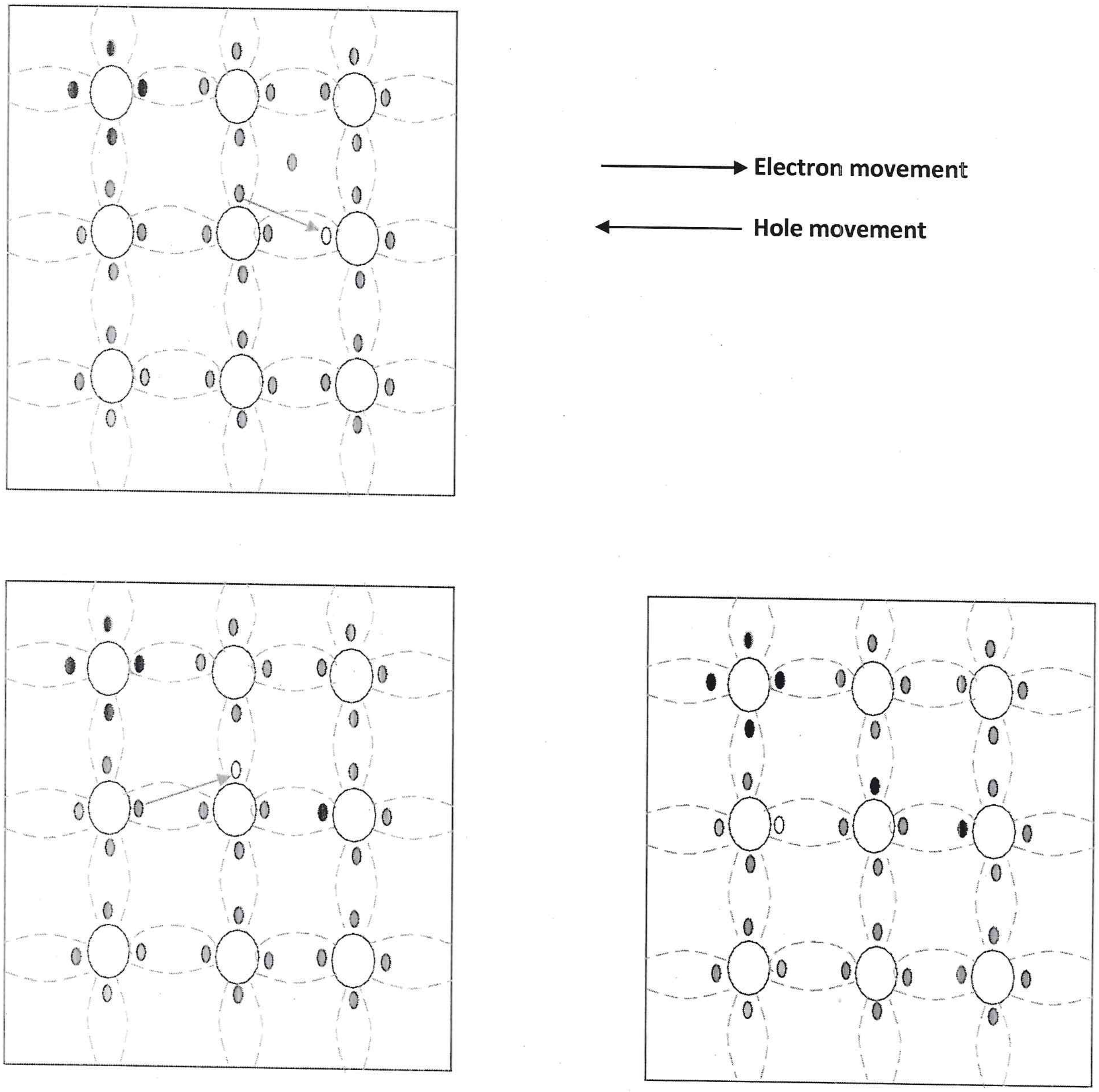


Crystal structure of Si at Room Temperature

(Break up of Covalent Bond)

- Absence of electrons in covalent bond acts as hole (Positive charge), carrier of electricity like free electron

- Valance electron in the neighboring atom leaves its covalent bond to fill this hole
- An electron moving from a bond to fill a hole moves in a direction opposite to that of the electron and process continues



INTRINSIC SEMICONDUCTOR:

- Intrinsic semiconductor conduct very small amounts of current at room temperature

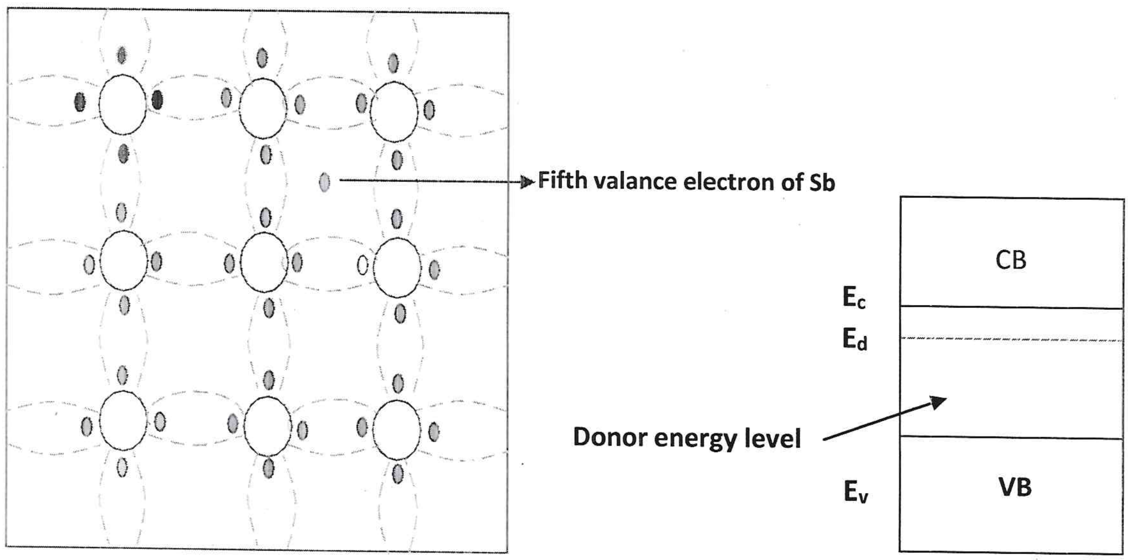
- The current conduction capability of intrinsic semiconductor can be increased significantly by adding a small amounts impurity as doping

- The amount of impurity added is 1 part in 10^6 atoms.

EXTRINSIC SEMICONDUCTOR:

N type semiconductor:

- Pentavalent atom (Phosphorus, Arsenic, Bismuth, Antimony) doped to the Intrinsic semiconductor (Si/Ge) results N Type semiconductor



Crystal structure and Energy band diagram

N type Semiconductor

- Doping creates donor energy level in the forbidden band gap, E_d slightly less than the conduction band energy

- The difference of conduction band and donor energy is the energy required to free the fifth valance electron (0.01 eV for Ge and 0.05 eV for Si)

- At room temperature, almost all the fifth electrons from the donor impurity atom are raised to conduction band

- The number of electrons in theconduction band increases significantly

- In the N-type semiconductor, the number of electrons increases but the number of holes decreases compared to intrinsic semiconductor

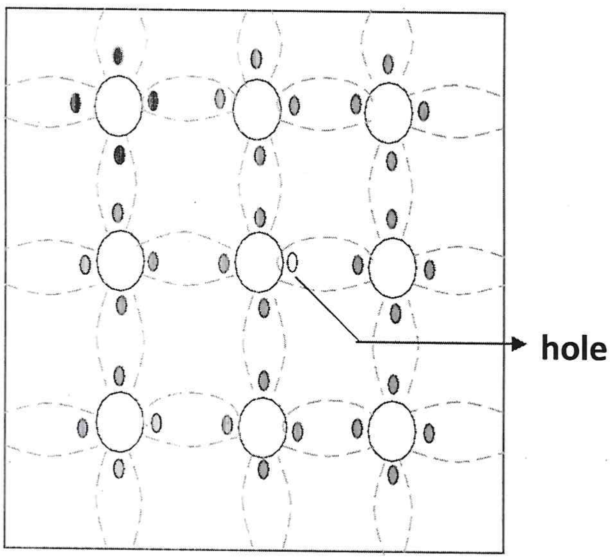
- It increases the recombination of electrons with holes

- Thus current in N type semiconductor is dominated by electrons as majority carriers

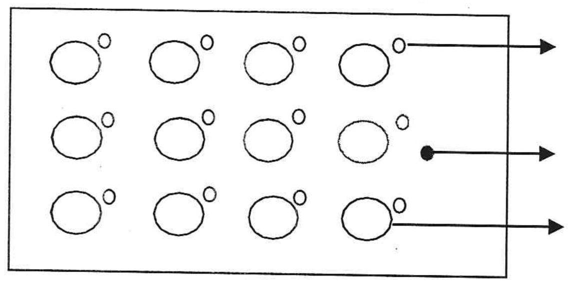
- Holes are the minority carriers in N type semiconductor

P type semiconductor:

- Trivalent atom (Boron, Gallium, indium) doped to the Intrinsic semiconductor (Si/Ge) results P Type semiconductor
- The three valance electrons of the impurity forms three covalent bonds with the neighboring atoms
- Vacancy in the fourth bond contributes holes
- Each trivalent atom contributes one hole generation and thus introduces a large number of holes in the Valance Band
- As a result number of electron decreases as compared to intrinsic semiconductor
- As a result, holes become majority carrier and electrons become minority carrier in P Type Crystal



Crystal structure of P type semiconductor



Crystal structure of P type semiconductor

- The conductivity of N type semiconductor is greater than that of P type as the mobility of electron is greater than hole
- For the same level of doping, the conductivity of an N type semiconductor is around twice that of a P type

CONDUCTIVITY OF SEMICONDUCTOR

- In a pure semiconductor, the number of holes is equal to the number of electrons
- Thermal agitation continue to produce new electron- hole pairs
- The electron - hole pairs disappear because of recombination
- With each electron hole pair created , two charge carrying particles are formed
- One is free electron with mobility μ_n and other is hole with mobility μ_p
- The electrons and holes move in opposite direction in a an electric field E

Since they are of opposite sign, the current due to each is in the same direction

- Total current density J within the intrinsic semiconductor

$$J = J_n + J_p = q N \mu_n E + q P \mu_p E = (N \mu_n + P \mu_p) q E = K E$$

Where $K = (N \mu_n + P \mu_p) q$

- N is the number of electrons / unit volume
- P is the number of holes / unit volume
- E is the applied electric field strength (V/m)
- q is the charge of electron or hole in Coulombs
- Hence, K is the conductivity of semiconductor is equal to $(N \mu_n + P \mu_p)q$
- The resistivity, R of semiconductor is reciprocal of conductivity.

  $R = 1/K$

- Current density within a semiconductor is directly proportional to applied electric field E.
- For pure semiconductor, $N = P = N_i$ where N_i = Intrinsic concentration

$N_i^2 = AT^3 \exp(-E/KT)$

$J = N_i (\mu_n + \mu_p) q E$

- Hence conductivity in intrinsic semiconductor is $K = N_i (\mu_n + \mu_p) q$
- Intrinsic conductivity increases at the rate of

5% per ° C for Ge and 7% per ° C for Si.

Conductivity in extrinsic semiconductor (N Type and P Type):

The conductivity of intrinsic semiconductor

$K = N_i (\mu_n + \mu_p) q = (N \mu_n + P \mu_p)q$

For N type , N >> P

$K = N q \mu_n$

For P type

P >> N

$K = P q \mu_p$

CHARGE DENSITIES IN P TYPE AND N TYPE SEMICONDUCTOR:

Law of Mass Action:

- Under thermal equilibrium for any semiconductor
- The product of the number of holes and the concentration of electrons is constant
- It is independent of amount of donor and acceptor impurity doping

$$N \cdot P = N_i^2$$

- In N type semiconductor, as the number of electrons increase the number of holes decreases

- In P type semiconductor, number of holes increases the number of electrons decreases

- Thus the product is constant and is equal to n^2 in case of intrinsic as well as extrinsic semiconductor

- The law of mass action has given the relationship between free electrons concentration and hole concentration

- These concentrations are further related by the law of electrical neutrality as explained

Law of electrical neutrality:

Semiconductor materials are electrically neutral

- According to the law of electrical neutrality, in an electrically neutral material, the magnitude of positive charge concentration is equal to negative charge concentration

- N_D donor atoms per cubic centimeter and N_A acceptor atoms per cubic centimeter, the concentration of donor and acceptor atoms are N_D and N_A respectively

- N_D positively charged ions per cubic centimeter are contributed by donor atoms and N_A negatively charged ions per cubic centimeter are contributed by the acceptor atoms

- Let n, p is concentration of free electrons and holes respectively. Then according to the law of electrical neutrality

$$N_D + p = N_A + n$$

- N type semiconductor, $N_A = 0$ and $n >> p$. Therefore, $N_D \approx n$
- N type semiconductor, the free electron concentration is approximately equal to the concentrationof donor atoms
- Some confusion may arise as to which type of semiconductor is under consideration, the subscript n or p is for N type or P type respectively

  Current density N type semiconductor

  $J = N_D \mu_n q E$

  Conductivity $K = N_D \mu_n q$

P type semiconductor, $N_D = 0$ and $p>>n$. Therefore $N_A \approx p$

- P type semiconductor, the hole concentration is approximately equal tc the concentration ofacceptor atoms
- Current density in N type

  semiconductor

- $J = N_A \mu_p q E$
- Conductivity $K = N_A \mu_p q$

- Mass action law for N type semiconductor,

$n_n \; p_n = n_i^2$

$p_n = n_i^2/N_D$

as $(N \approx N_D)$

- Law of Mass action for P type semiconductor

$n_p \; p_p = n_i^2$

$n_p = n_i^2/ N_A$ as $(P \approx N_A)$

QUANTITATIVE THEORY OF PN JUNCTION DIODE:

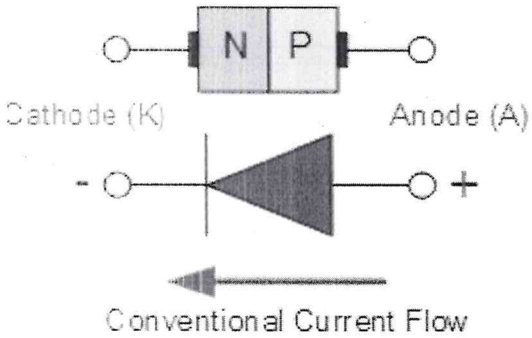
PN JUNCTION WITH NO APPLIED VOLTAGE:

- one half doped by p type impurity and the other half doped by n type impurity, a PN junction is formed
- The plane dividing the two halves or zones is called PN junction
- The n type material has high concentration of free electrons
- p type material has high concentration of holes
- At the junction there is a tendency of free electrons to diffuse over to the P side and the holes to the N side. This process is called diffusion
- The free electrons move across the junction from N type to P type, the donor atoms become positively charged
- Positive charge is built on the N-side of the junction
- The free electrons that cross the junction uncover the negative acceptor ions by filing the holes
- Negative charge is developed on the p side of the junction
- This net negative charge on the p side prevents further diffusion of electrons into the p side
- The net positive charge on the N side repels the hole crossing from p side to N side
- Thus a barrier is set up near the junction which prevents the further

movement of charge carriers i.e. electrons and holes

- Induced electric field across the depletion layer, an electrostatic potential difference is established between P and N regions, which are called the potential barrier, junction barrier, diffusion potential or contact potential

- The magnitude of the contact potential varies with doping levels and temperature, 0.3V for Ge and 0.72 V for Si



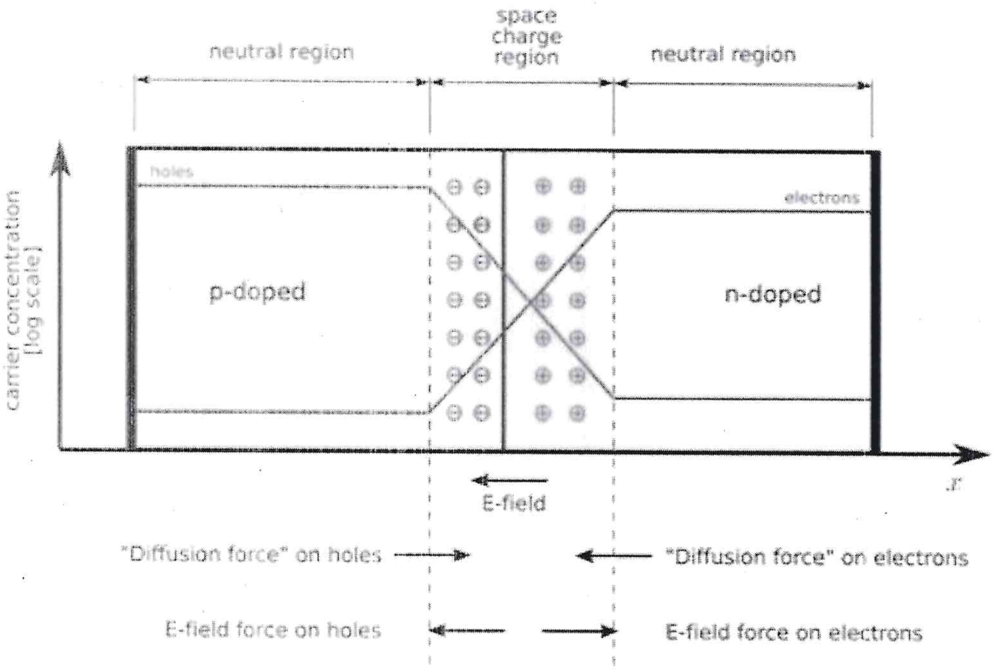
Symbol of PN Junction Diode

- Electrostatic field, positively charged N-Type region tends to drive the holes away from the junction

- Negatively charged p type regions tend to drive the electrons away from the junction

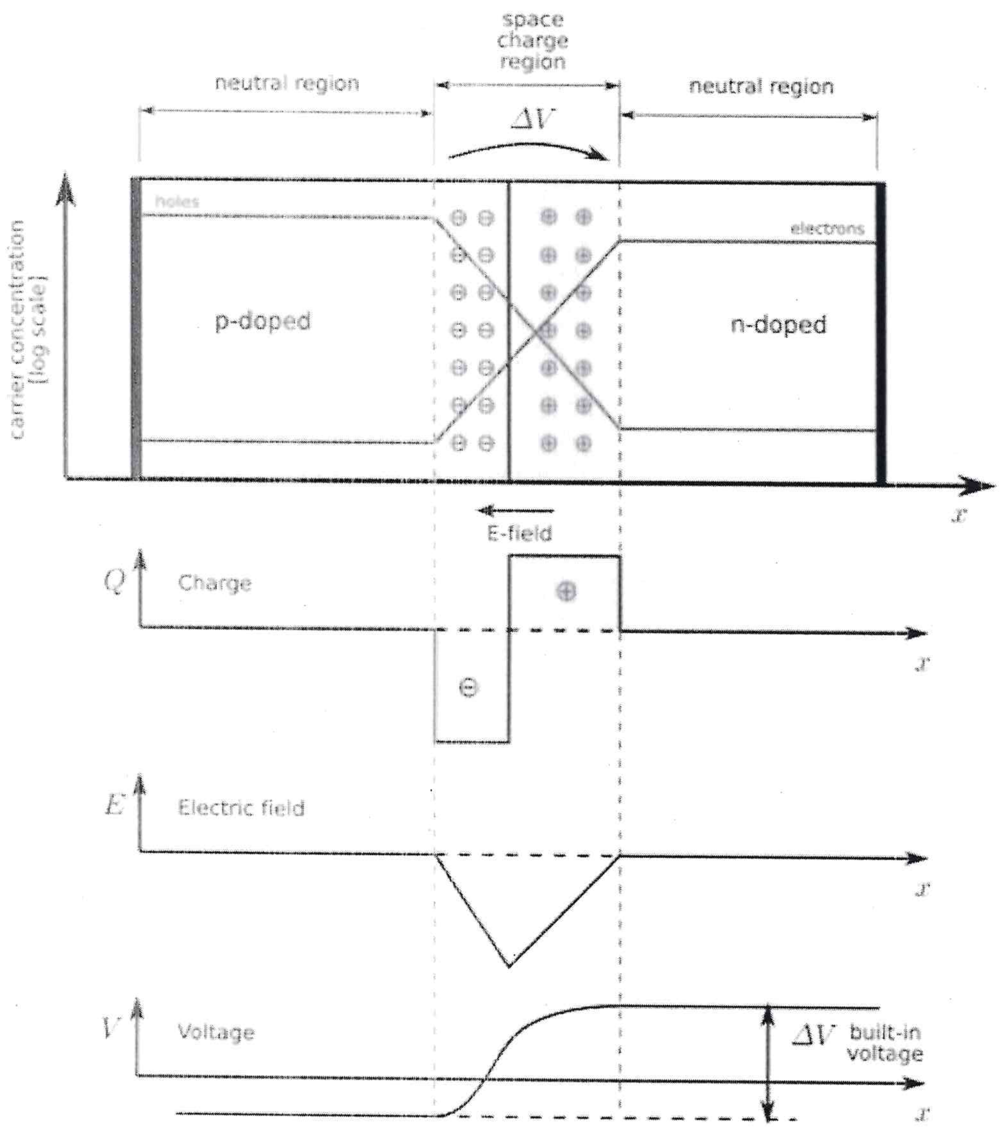
- The majority holes diffusing out of the P region leave behind negatively charged acceptor atoms bound to the lattice
- Exposing a negative space charge in a previously neutral region

- Electrons diffusing from the N region expose positively ionized donor atoms and a double space charge builds up at the junction



- Space charge layers are of opposite sign to the majority carriers diffusing into them tends to reduce the diffusion rate
- The double space of the layer causes an electric field to be set up across the junction directed from N to P regions
- A directionto inhibit the diffusion of majority electrons and holes
- The shape of the chargedensity, ρ depends upon doped
- the junction region, depleted of mobile charge carriers
- It is called depletion layer, space region, and transition region
- The depletion region isof the order of 0.5µm thick
- No mobile carriers in this narrow depletion region
- The system is in equilibrium

- Left of this depletion layer, the carrier concentration is $p = N_A$
- In right, it is $n = N_D$

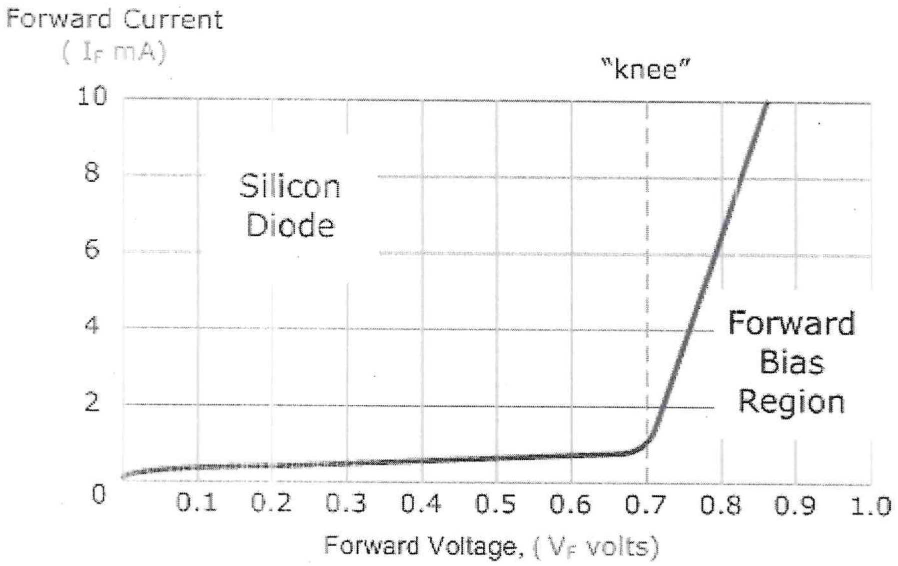


FORWARD BIASED JUNCTION DIODE

Forward Bias condition:

- A negative voltage is applied to the N- type material
- Positive voltage is applied to the P-type material
- This external voltage, 0.7 volts for silicon and 0.3 volts for germanium
- The potential barriers opposition will be overcome and current will start to flow.
- The negative voltage pushes or repels electrons towards the junction giving them the energy to cross over
- Combine with the holes being pushed in the opposite direction towards the junction by the positive voltage
- The characteristics curve of zero current flowing up to this voltage point called the "knee" on the static curves
  - High current flow through the diode with little increase in the external voltage

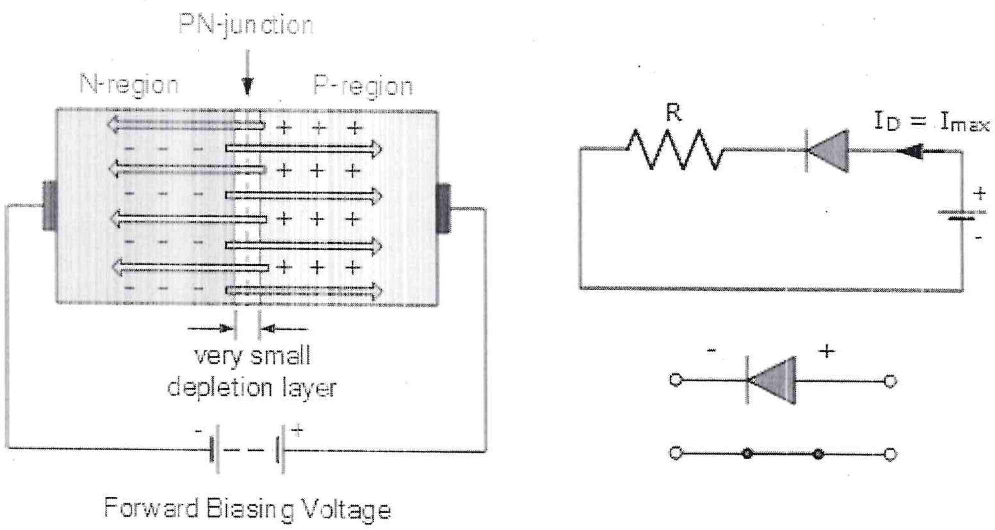
Forward Characteristics Curve for a Junction Diode



Diode Forward Bias Characteristics

- **Forward biasing voltage on the junction diode lead to:**
- **The depletion layer becomes very thin and narrow**
- **A low impedance path through the junction high currents to flow**
- **This increase in current on the static I-V characteristics curve above as the "knee" point**

Forward Biased Junction Diode shows a Reduction in the Depletion Layer



Diode Forward Bias

- Low resistance path through the PN junction allowing very large currents to flow through the diode with only a small increase in bias voltage

- The actual potential difference across the junction or diode is kept constant by the action of the depletion layer at approximately 0.3V for germanium and approximately 0.7V for silicon junction diodes

- The diode can conduct "infinite" current above this knee point as it effectively becomes a short circuit

- One resistor is used in series with the diode to limit its current flow

- Exceeding its maximum forward current specification causes the device to dissipate more power in the form of heat than it was designed for resulting in a very quick failure of the device.

PN JUNCTION UNDER REVERSE BIAS

Reverse Biased Junction Diode:

- Reverse Bias condition, a positive voltage is applied to the N-type materi and a negative voltage is applied to the P-type material

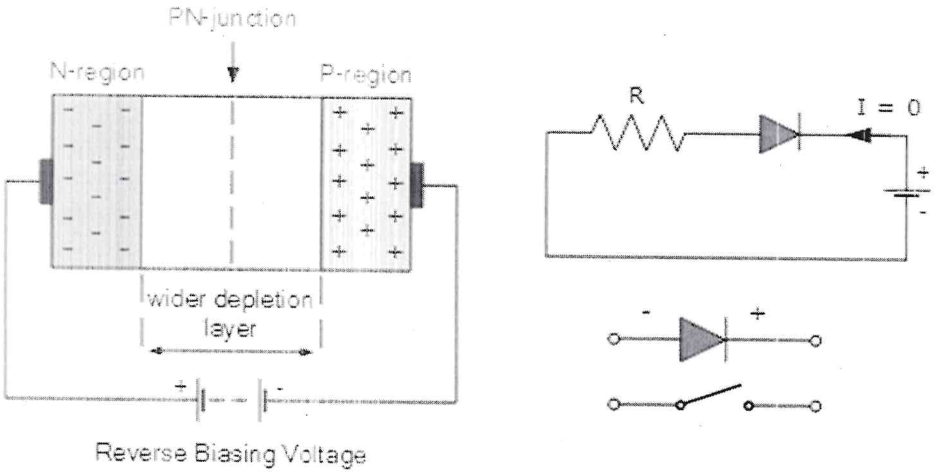
- The positive voltage applied to the N- type material attracts electro towards the positive electrode and away from the junction

- The holes in the P-type are also attracted away from the junction towar the negative electrode

- The net result is that the depletion layer grows wider due to a lack electrons and holes presents a high impedance path, almost an insulator

- The result is that a high potential barrier is created thus preventing curre from flowing through the semiconductor material.

Reverse Biased Junction Diode showing an Increase in the Depletion



Diode Reverse Bias

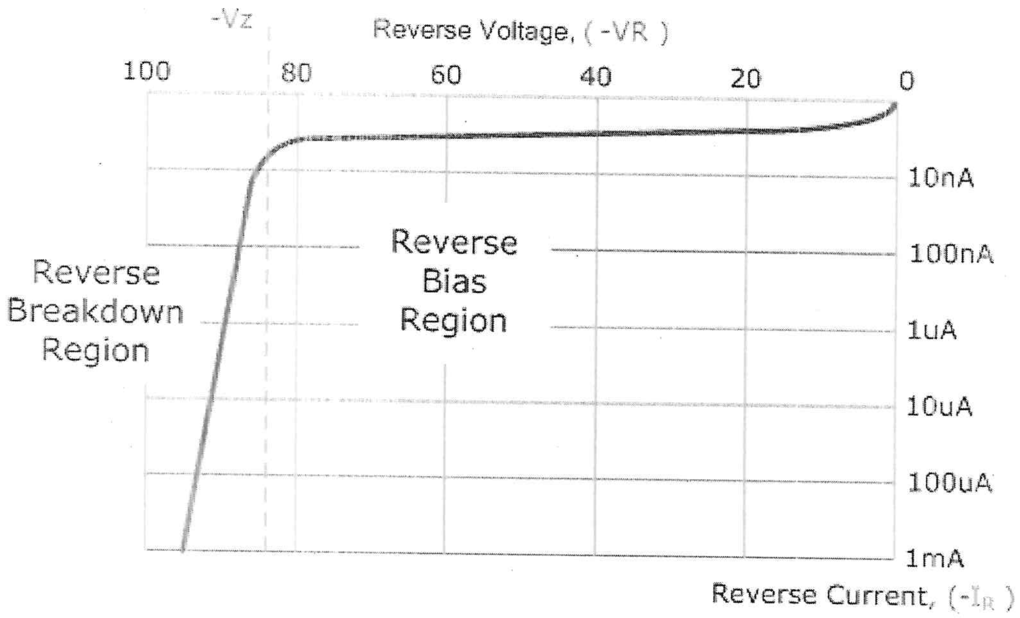
- This condition represents a high resistance value to the PN junction and practically zero current flows through the junction diode with an increase in bias voltage

- A very small leakage current does flow of the order of microamperes

- One final point, if the reverse bias voltage applied to the diode is increased to a sufficiently high enough value, it will
- cause the PN junction to overheat fail due to the avalanche effect around the junction

- This maycause the diode to become shorted and will result in the flow of maximum circuit current, and this shown as a step downward slope in the reverse static characteristics curve below

- Reverse Characteristics Curve for a Junction Diode



Diode Reverse Characteristics

- This avalanche effect has practical applications in voltage stabilizing circuits

- A series limiting resistor is used with the diode to limit this reverse breakdown current to a preset maximum value

- Producing a fixed voltage output across the diode. These types of diodes are commonly known as Zener Diodes

VI CHARACTERISTICS AND TEMPERATURE DEPENDENCE

Diode terminal characteristics equation for diode junction current:

$$I_D = I_0(e^{\frac{V_D}{\eta V_T}} - 1)$$

V_T : KT/q

V_D : Diode Terminal Voltage

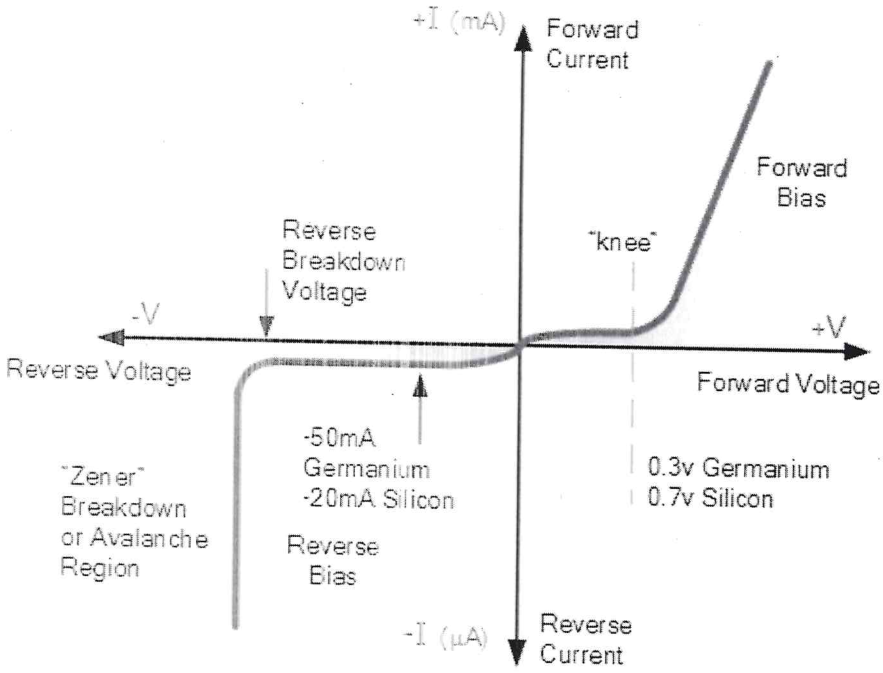
I_0: Temperature-dependent saturation current, µA

T: Absolute Temperature of P – N junction in Kelvin

K: Boltzmann's constant 1.38x 10 -23J/K)

q: Electron charge 1.6 x 10-19 C

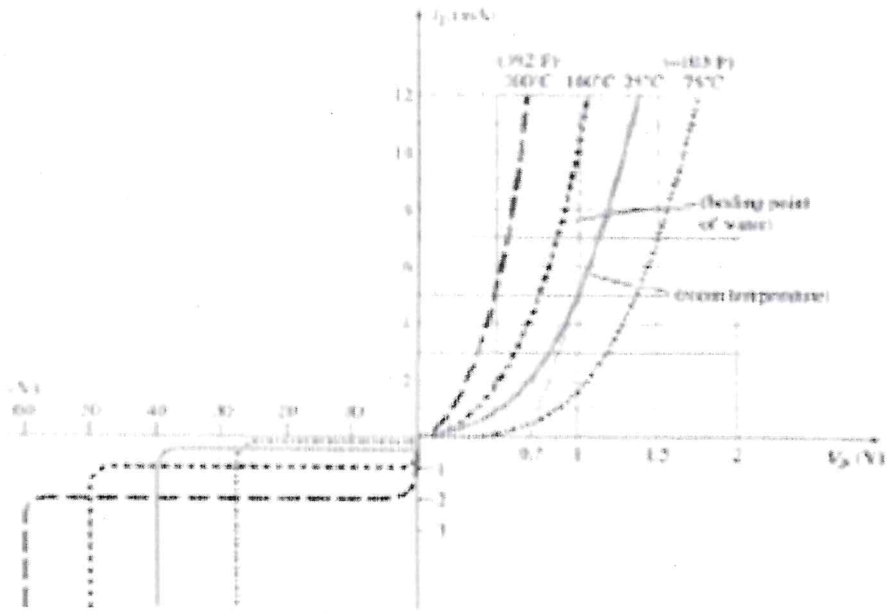
η = empirical constant, 1 for Ge and 2 for Si



Diode Characteristics

Temperature Effects on Diode:

- Temperature can have a marked effect on the characteristics of a silicon semiconductor diode.
- It has been found experimentally that the reverse saturation current I_o will just about double in magnitude for every 10°C increase in temperature.



Variation in Diode Characteristics with temperature change

- Germanium diode with an I_o in the order of 1 or 2 A at 25°C to have a leakage current of 100 A - 0.1 mA at a temperature of 100°C

- Typical values of I_o for silicon are much lower than that of germanium for similar power and current levels

- The result is that even at high temperatures the levels of I_o for silicon diodes do not reach the same high levels

- For germanium, a very important reason that silicon devices enjoy a significantly higher level of development and utilization in design

- The open-circuit equivalent in the reverse bias region is better realized at any temperature with silicon than with germanium

- The increasing levels of I_o with temperature account for the lower levels of threshold voltage

- Increase in the level of I_o but not rise in diode current

- As the temperature increases the forward characteristics are actually becoming more "ideal,"

IDEAL VERSUS PRACTICAL RESISTANCE LEVELS

DC or Static Resistance

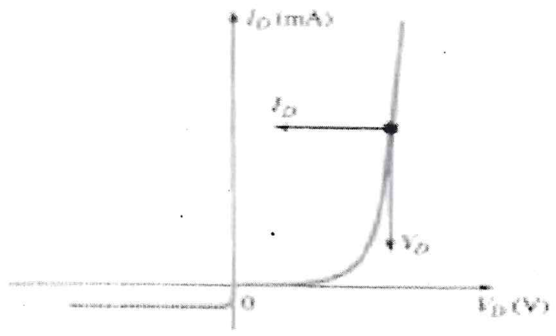
- The application of a dc voltage to a circuit containing a semiconductor diode will result in an operating point on the characteristic curve that will not change with time

- The resistance of the diode at the operating point can be found simply by finding the corresponding levels of V_D and I_D

- $$\boxed{R_D = \frac{V_D}{I_D}}$$

- The dc resistance levels at the knee and below will be greater than the resistance levels obtained forthe vertical rise section of the characteristics

- The resistance levels in the reverse-bias region will naturally be quite high



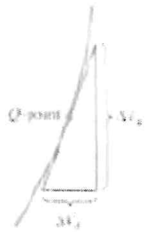
Determining the dc resistance of a diode at a particular operating point.

AC or Dynamic Resistance

- The dc resistance of a diode is independent of the shape of the characteristic
- If a time variable signal is applied, the situation will change completely. The varying input will move the instantaneous operating point up and down a region of the characteristics
- It defines a specific change in current and voltage. *A straight-line drawn tangent to the curve through the Q-point will define* a particular change in voltage and current that can be used to determine the ac or dynamic resistance for this region of the diode characteristics

$$\boxed{r_d = \frac{\Delta V_d}{\Delta I_d}}$$

Where Δ Signifies a finite change in the quantity



Determining the ac resistance of a diode at a particular operating point

DIODE EQUIVALENT CIRCUITS

- An equivalent circuit is a combination of elements properly chosen to best represent the actual terminal characteristics of a device, system, or such in a particular operating region

- Once the equivalent circuit is defined, the device symbol can be removed from a schematic and the equivalent circuit inserted in its place without severely affecting the actual behavior of the system

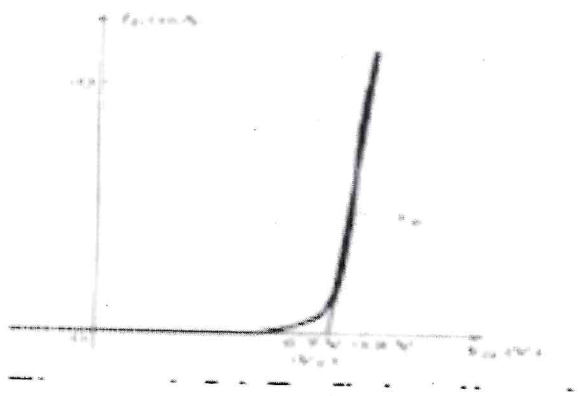
Piecewise-Linear Equivalent Circuit

- One technique for obtaining an equivalent circuit for a diode is to approximate the characteristics of the device by straight-line segments

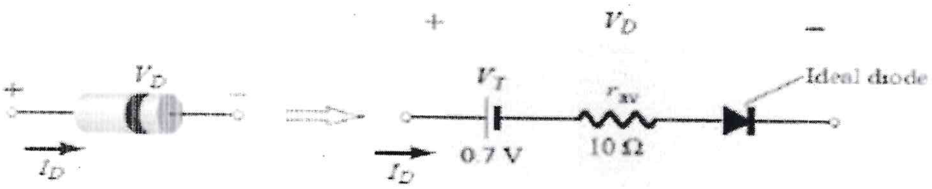
- The resulting equivalent circuit is naturally called the piecewise-linear equivalent circuit. It should be obvious that the straight-line segments do not result in an exact duplication of the actual characteristics, especially in the knee region

- The resulting segments are sufficiently close to the actual curve to establish an equivalent circuit that will provide an excellent first approximation to the actual behavior of the device

- The ideal diode is included to establish that there is only one direction of conduction through the device
- A reverse-bias condition will result in the open- circuit state for the device
- Since a silicon semiconductor, diode does not reach the conduction state until V_D reaches 0.7 V with a forward bias
- Conduction is established, the resistance of the diode will be the specified value of r_{av}.

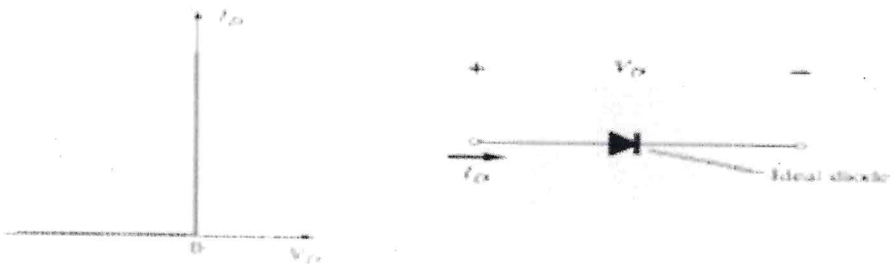


Diode piecewise-linear model characteristics

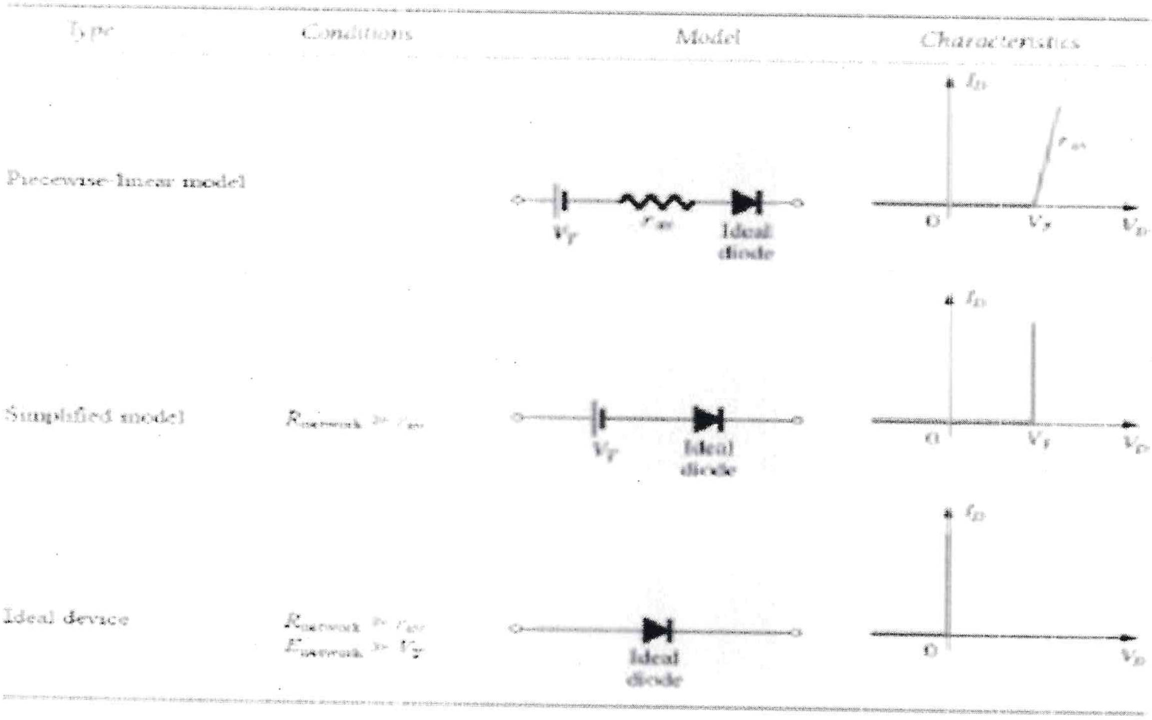


Diode piecewise-linear model equivalent circuit

- The approximate level of r_{av} can usually be determined from a specified operating point on thespecification sheet



Ideal Diode and its characteristics



Diode equivalent circuits (models)