BASIC ELECTRONICS
EC-13101

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PRINCIPLES OF ELECTRONICS ENGINEERING (EC-1301)

UNIT 1: Diodes- Introduction to *pn* diode and its applications as rectifier, rectifier as DC Power Supply, Clamper, Clipper, Voltage multiplier etc., Zener diode and its applications as regulator, Tunnel diode and Varactor diode. 8(L)

UNTI 2: Transistors-Review of Transistor working, characteristics & its parameters, Transistor as an amplifier, Biasing of bipolar junction transistors, *h*-parameters & transistor equivalent circuits, small signal single-stage amplifier, frequency response, concept of feedback. 8(L)

JFET and MOSFET Basic construction, working, concept of pinch-off, characteristics of JFET, MOSFET (Enhancement and Depletion), FET as a voltage variable resistor. 6(L)

UNIT3: Operational amplifier-Ideal & non-ideal characteristics, concept of summing junction and virtual ground. Application of operational amplifier as: Adder, Subtractor, Differentiator, Integrator, Multiplier, Unity gain amplifier & Logarithmic amplifier.

6(L)

UNIT 4 Introduction to Digital Electronics: Review of number systems, complements, codes, Boolean algebra, Logic gates, Minterm and Maxterms, Canonical and Standard forms, Logic functions & Logic circuits. Minimization of Boolean functions using K-map.

6(L)

UNIT 5 Measuring Instruments: Working of Cathode Ray Oscilloscope, Power supply, Multimeter and Function generator

6(L)

Text/ Reference Books:

1. Electronic devices and circuit theory by Robert Boylested and Louis Nashelsky
2. Electronic principles by Albert Malvino
3. Integrated Electronics by Jacob Millman, Chistos C. Halkias
4. Digital design by Morris Mano
5. Modern Digital Electronics by R. P. Jain
6. Modern electronics Instrumentation and Measurement Techniques by A. D. Helfrick and W. D. Cooper

UNIT I

DIODES

Contents

Introduction to *pn* diode and its applications as rectifier, rectifier as DC Power Supply, Clamper, Clipper, Voltage multiplier etc., Zener diode and its applications as regulator, Tunnel diode and Varactor diode.

Text book 1:
Robert L. Boylestad & **Louis Nashelsky, "Electronic Devices and Circuit Theory",** 10th Edition, Pearson Education, 2013.
Text book 2:
Integrated Electronics by Jacob Millman, Chistos C. Halkias

Introduction

Q: What is Electronics Engineering?

Ans: The word **e**lectro**n**ics derives its name from the words **ELECTRO**N and MECHA**NICS**.

Electronics Engineering is the technology associated with low voltage, current and semiconductor solid state integrated circuits, usually for transmission or processing of analog or digital data.

OR

It is a field of science and engineering, which deals with **electronic devices** and their utilization.

Q: What is Electronic Device**?**

Ans: A device in which conduction takes place by the movement of **electrons** through a **vacuum, gas** or a **semiconductor.**

Important functions of Electronics

The electronics has great importance in todays world as electronic devices are capable of doing many functions:

- **Rectification** (AC to DC conversion)
- **Amplification**
- **Control** (Automatic Control System)
- **Generation**
- **Conversion of light into electricity & vice-versa**

Applications of Electronics

- **Communication**

(i) wired e.g. Telegraph, Telephone, Telefax

(ii) wireless e.g. Radio Broadcasting, TV Broadcasting, Satellite communication

- **Entertainment (Audio & Video)**
- **Defence Applications**

(i) RADAR (**RA**dio **D**etection **A**nd **R**anging) – it gives exact position of enemy aircraft.

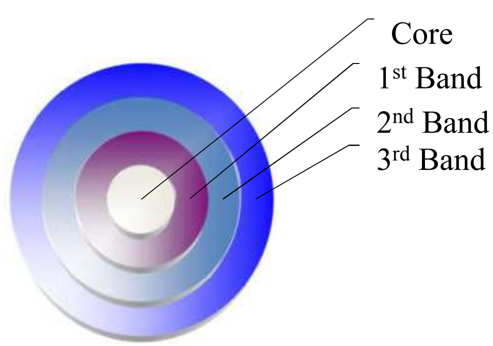
(ii) Guided Missiles (completely controlled by electronic circuits)

- **Industrial applications**
- **Medical Sciences** (X-RAY, ECG, OSCILLOGRAPHS-for Muscle action)
- **INSTRUMENTATION** (CRO, FREQUENCY COUNTER, FUNCTION GENERATORS)

Atomic Structure

- **Energy Band:** The range of energies possessed by an electron in a solid.
- There are two energy bands in solids:

1. **Valence Band:** The range of energies possessed by **valence electrons.**
2. **Conduction Band:** The range of energies possessed by **free electrons (conduction electrons).**



TRIVALENT, TETRAVALENT, PENTAVALENT ATOMS

III (TRIVALENT) (ACCEPTOR ATOM)	IV (TETRAVALENT)	V (PENTAVALENT) (DONOR ATOM)
B	C	N
Al	**Si**	**P**
Ga	**Ge**	**As**
In	Sn	**Sb**
Th	Pb	**Bi**

Q. C (carbon) is in semiconductor group but is is an insulator, why?

Spin configuration of different atoms

C (Z=6) $1s^2$, $2s^2$, $2p^2$ **(2, 4)**

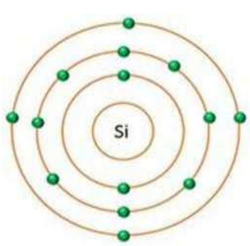
Si (Z=14) $1s^2$, $2s^2$, $2p^6$, $3s^2$, $3p^2$ **(2, 8, 4)**

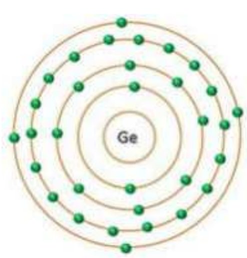
Ge (Z=32) $1s^2$, $2s^2$, $2p^6$, $3s^2$, $3p^6$, $4s^2$, $3d^{10}$, $4p^2$ **(2, 8, 18, 4)**

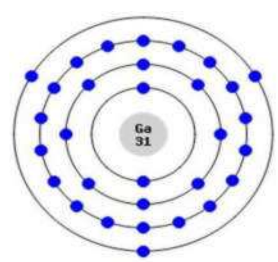
....

Ga (Z=31) $1s^2$, $2s^2$, $2p^6$, $3s^2$, $3p^6$, $4s^2$, $3d^{10}$, $4p^1$ **(2, 8, 18, 3)**

As (Z=33) $1s^2$, $2s^2$, $2p^6$, $3s^2$, $3p^6$, $4s^2$, $3d^{10}$, $4p^3$ **(2, 8, 18, 5)**



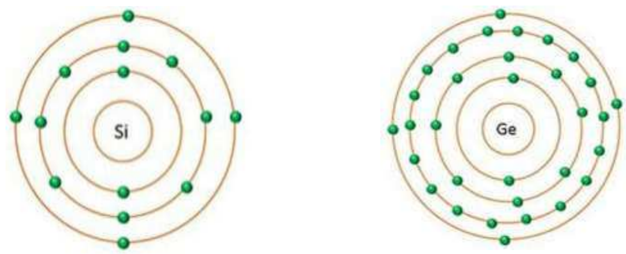




Why Si is preferred over Ge?

Si (Z=14) $1s^2$, $2s^2$, $2p^6$, $3s^2$, $3p^2$ **(2, 8, 4)**

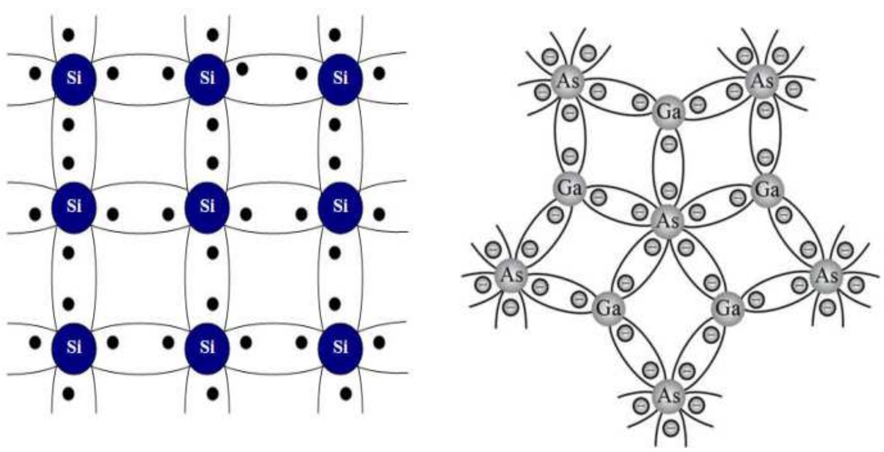
Ge (Z=32) $1s^2$, $2s^2$, $2p^6$, $3s^2$, $3p^6$, $4s^2$, $3d^{10}$, $4p^2$ **(2, 8, 18, 4)**



- Si is preferred over Ge due to the following reason:

i) High current rating
ii) High temperature stability
iii) Small leakage current (in nA)
iv) Easily available and extractable

Covalent Bonding of Si & GaAs



Comparison of Si, Ge and GaAs semiconductors

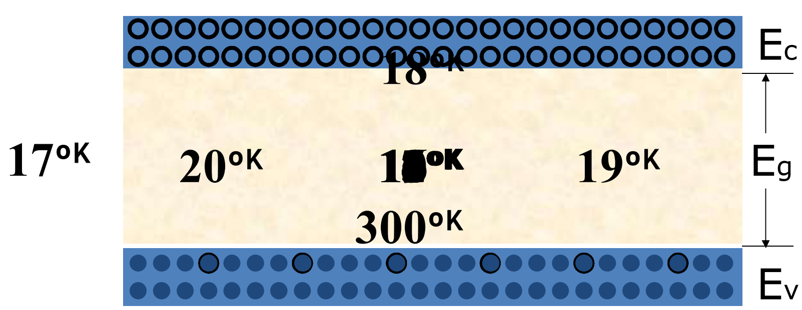
Semiconductor	Intrinsic Carriers (n_i in per cubic centimeter)	Band Gap (E_g in eV)	Electron Mobility (μ_n in $cm^2/V\text{-}s$)
Si	1.5×10^{10}	1.1	1500
Ge	2.5×10^{13}	0.67	3900
GaAs	1.7×10^{6}	1.43	8500

$$\text{ELECTRON MOBILITY}(\mu_n) = \frac{\text{DRIFT VELOCITY } (V_D \text{ in } m/s)}{\text{ELECTRIC FIELD INTENSITY } (E \text{ in } v/m)}$$

Note:

Semiconductor materials have
Negative Temperature Coefficient
(wrt Resistance)

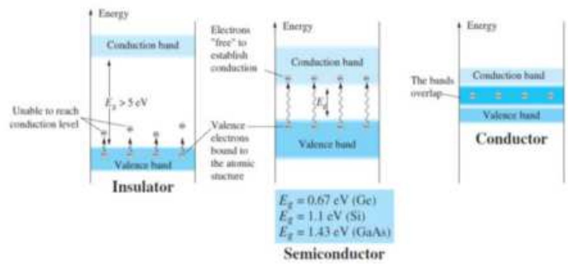
Carriers in Semiconductor



Electron Hole Pair

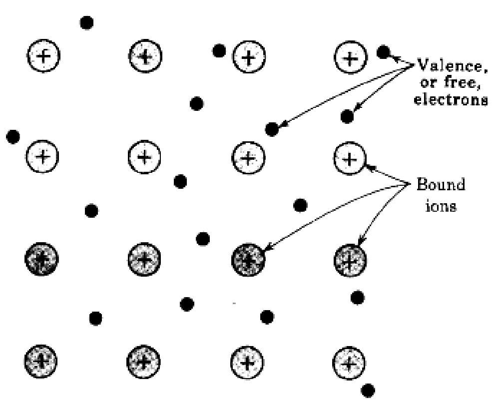
Classification of Solids

The energy band diagram for the three types of solids are:



1. Insulator e.g. C, wood, plastic etc.
2. Semiconductor e.g. Si, Ge etc.
3. Metal (Conductor) e.g. Cu, Al, Au etc.

Mobility and conductivity

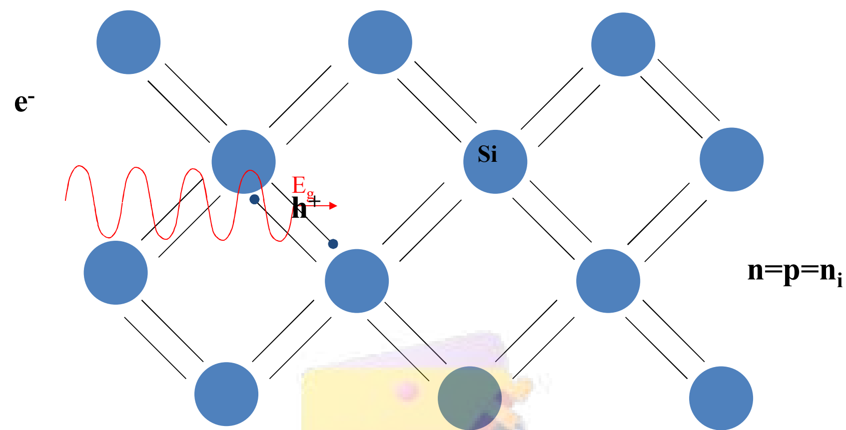


Electron Gas
Mean free path
Drift speed, v
Speed between the collison
=at where a=qE/m
Average speed, v=μE
Square meter per volt-second

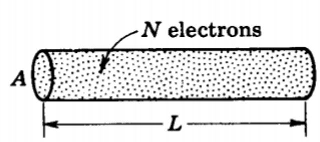
Type of Semiconductors

1. Intrinsic (pure) Semiconductor

Semiconductors in extremely pure form

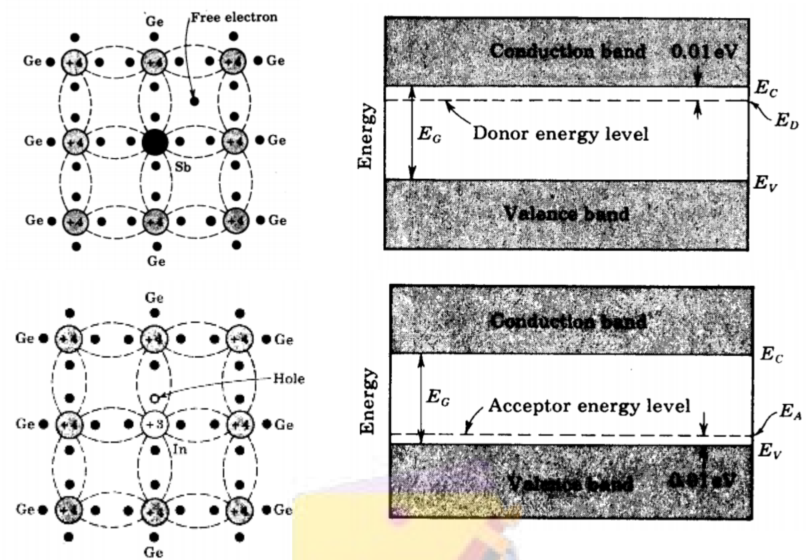


Current Density

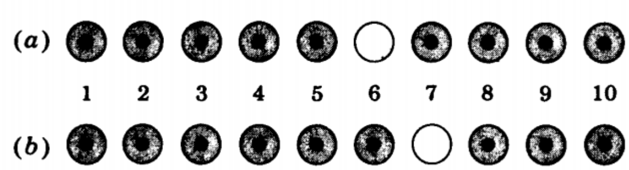


Electrons crossing through a cross section area in unit time = **N/T**
Total charge passing any area per unit time = **qN/T**=Current
Since, drift velocity, **v=L/T => T=L/v**
i.e., **I = qNv/L**
Current density, **J = current per unit area = I/A**
(assuming uniform current distribution)
J=qNv/LA = nqv
where, n = number of electrons per unit volume = N/LA = **carrier density (electron density)**
ρ=nq = charge density => **J= ρv** (independent of conducting medium)
[ρ and v both may vary with time and point to point in space]
J= ρv = nqv = nqμE=σE (Ohm's Law)
Conductivity = **σ = nqμ** $[\text{ohm-meter}]^{-1}$
Power density = **Jσ = σE²**

Donor and Acceptor



Hole concept



Free electron
Hole
Effective mass
Donor and acceptor impurities

Mass Action Law

In intrinsic semiconductor:

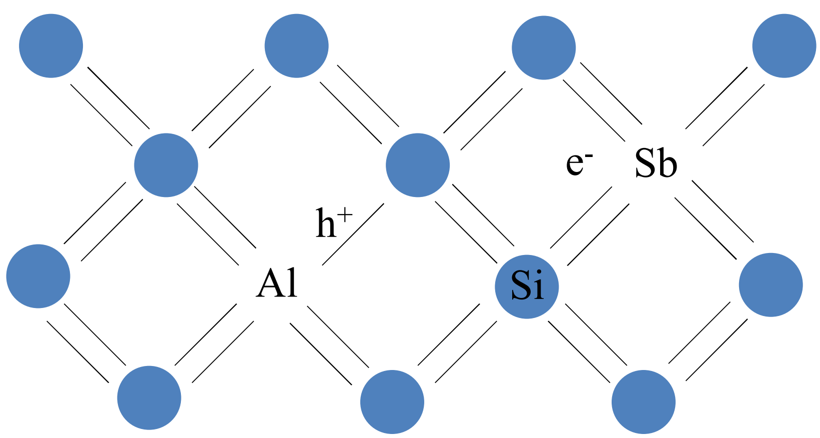
Adding n type impurities reduces hole concentration &
Adding p type impurities reduces electron concentration
Under thermal equilibrium condition

Product of negative and positive charges remains constant irrespective of the acceptor/donor impurity doping, i.e.,

$$n.p=(n_i)^2$$

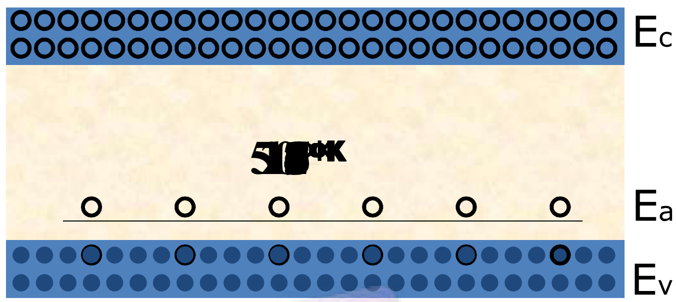
2. Extrinsic (impure) Semiconductor (P & N Type)

- In order to increase conductivity of intrinsic semiconductor we have add some impurity to the intrinsic semiconductor. The resultant is know as extrinsic type semiconductor.
- **Doping:** Adding of impurities (dopants) to the intrinsic semi-conductor material.
- **P-type:** Adding Group III dopant (or acceptor) such as B, Al, Ga, In …
- **N-type:** Adding Group V dopant (or donor) such as As, P, Sb, Bi …



Carriers in Extrinsic Semiconductor (P Type)

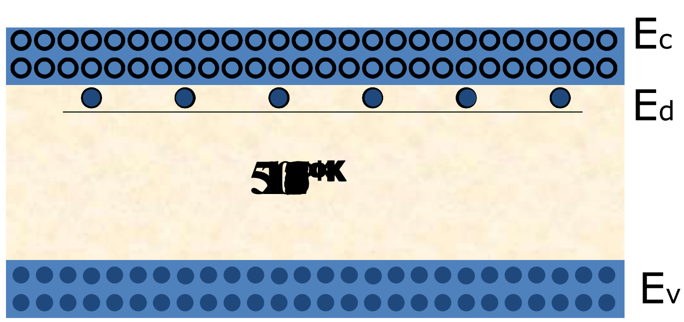
III Group
B
Al
Ga
In



Acceptor

Carriers in Extrinsic Semiconductor (N Type)

V Group
P
As
Sb



Donor

Charge Densities in Semiconductors

Relationship between electron and hole concentration:

$n.p=(n_i)^2$

Theses can be interrelated by **law of electrical neutrality**,

$N_D + p = N_A + n$

n-type, N_A=0 & n>>p; i.e. $n \approx N_D$ [Also written as: $n_n \approx N_D$]

p-type, N_D=0 & p>>n; i.e. $p \approx N_A$ [Also written as: $p_p \approx N_A$]

The minority charge carriers can be calculated using :

n-type, $n_n p_n = n_i^2$ => $p_n = n_i^2 / N_D$ $[\because n_n = N_D]$

p-type, $p_p n_p = n_i^2$ => $n_p = n_i^2 / N_A$ $[\because p_p = N_A]$

Electrical properties of Si & Ge

Current density due to electrons: $J_n = nq\mu_n E$

Current density due to holes: $J_p = pq\mu_p E$

Total current density: $J = J_n + J_p = (n\mu_n + p\mu_p)qE = \sigma E$

Conductivity: $\sigma = (n\mu_n + p\mu_p)q$

Energy Gap:

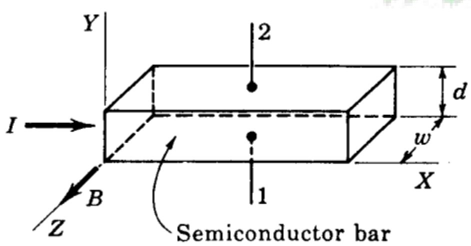
Si: $E_G(T) = 1.21 - 3.60 \times 10^{-4} T$ $@300K, E_G = 1.1 eV$

Ge: $E_G(T) = 0.785 - 2.23 \times 10^{-4} T$ $@300K, E_G = 0.72 eV$

Electrical properties of Si & Ge

Property	Ge	Si
Atomic number	32	14
Atomic weight	72.6	28.1
Density, g/cm^3	5.32	2.33
Dielectric constant (relative)	16	12
Atoms/cm^3	4.4×10^{22}	5.0×10^{22}
E_{GO}, eV, at 0°K	0.785	1.21
E_G, eV, at 300°K	0.72	1.1
n_i at 300°K, cm^{-3}	2.5×10^{13}	1.5×10^{10}
Intrinsic resistivity at 300°K, Ω-cm	45	230,000
μ_n, cm^2/V-s at 300°K	3,800	1,300
μ_p, cm^2/V-s at 300°K	1,800	500
D_n, $cm^2/s = \mu_n V_T$	99	34
D_p, $cm^2/s = \mu_p V_T$	47	13

Hall Effect



If a specimen carrying a current I is placed in a transverse magnetic field B, an electric field E is induced in the direction perpendicular to both I and B. This is Hall effect which can be used to determine the type of semiconductor and carrier concentration.

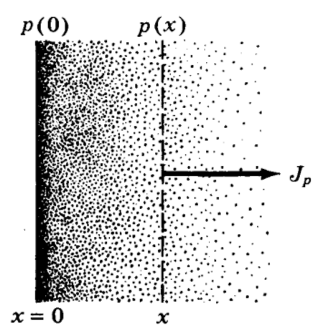
Determination of mobility

Current may be due to holes moving from left to right or due to electrons moving from right to left in the semiconductor specimen. Irrespective of carrier type, these are forced downward toward side 1 => This surface becomes negatively charged w.r.t. side 2. Due to this a potential called "Hall voltage, V_H" appears between surface 1 and 2.
If the polarity of V_H is +ve at terminal 2, then carriers must be electrons => semiconductor must be n-type.
If terminal 1 becomes charged +ve w.r.t. 2, semiconductor must be p-type.
This also verifies (experimentally) the bipolar nature of current in semiconductors.

$$qE = Bqv \qquad where\ \ E = V_H/d$$
$$V_H = Ed = Bvd = BJd/\rho$$
$$= BId/(wd\rho), [\because J = \rho v],$$

$$\rho = \text{charge density} \ \& \ R_H = 1/\rho = V_H w/(BI)$$
$$\sigma = nq\mu = \rho\mu \qquad \text{or} \qquad \mu = \sigma R_H$$

Diffusion



Diffusion occurs in semiconductors and not in metals.

Concentration Gradient = dp/dx

More carriers are transferred from higher concentration side as compared to that from lower concentration side => results in net transfer of carriers [This is statistical phenomenon]

Diffusion hole current is proportional to concentration gradient

$$J_p \propto q\left(\frac{dp}{dx}\right) \Rightarrow J_p = -qD_p \frac{dp}{dx}$$

Diffusion constant Dn (square meters per second).
Since *p* decreases with increasing x, hence gradient is negatiive.

Einstein Relationship

Since both diffusion and mobility are statistical thermodynamic phenomenon, D and μ are not independent. The relationship between these two is given by

$$\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = V_T \qquad V_T = \frac{kT}{q} = \frac{T}{11,600}$$

Where, V_T is "volt-equivalent temperature"
It is 0.026 V @ 300 K.

$$\mu = 39D$$

Total current

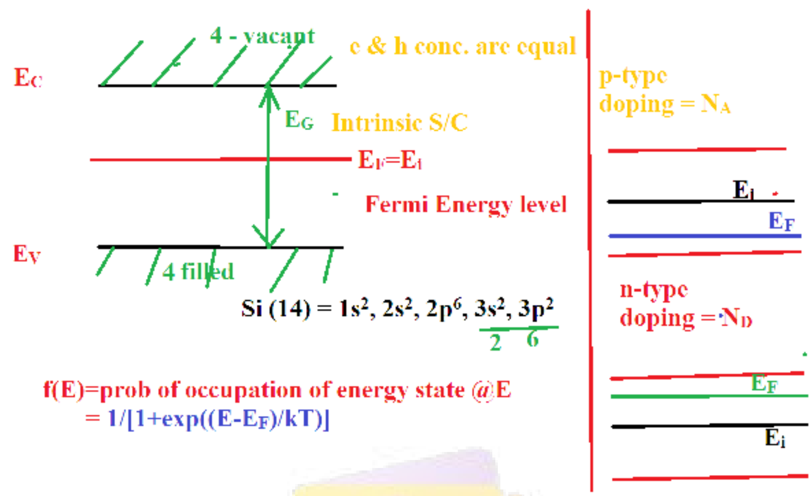
If the potential gradient and concentration gradient exists simultaneously within semiconductor, then total hole current will be sum of drift current and diffusion current, i.e.,

$$J_p = q\mu_p pE - qD_p \frac{dp}{dx}$$

Similarly, the total electron current is given by

$$J_n = q\mu_n nE + qD_n \frac{dn}{dx}$$

Energy Band diagram of n/p type S/C



f(E)=prob of occupation of energy state @E
= $1/[1+\exp((E-E_F)/kT)]$

Graded semiconductor

(a)Graded S/C (b) p-n junction

Because of non-uniform doping, there exists an electric field within the semiconductor.

$$J_p = q\mu_p p(x)E - qD_p \frac{dp(x)}{dx} = 0 \Rightarrow E = \frac{D_p}{\mu_p}\frac{1}{p(x)}\frac{dp(x)}{dx}$$

$$J_n = q\mu_n n(x)E + qD_n \frac{dn(x)}{dx} = 0 \Rightarrow E = -\frac{D_n}{\mu_n}\frac{1}{n(x)}\frac{dn(x)}{dx}$$

Graded semiconductor

$$n(x) = n_0 \exp(-bx) \quad \left[\text{Using } \; D_n/\mu_n = D_p/\mu_p = V_T = kT/q\right]$$

$$E(x) = -\frac{D_n}{\mu_n}\frac{1}{n(x)}\frac{dn(x)}{dx} = -\frac{kT}{q}\frac{1}{n_0 \exp(-bx)}\left[-n_0 b \exp(-bx)\right] == \frac{kT}{q} b$$

$$E(x) = -dV/dx \Rightarrow dV = -E(x)\,dx = \frac{D_n}{\mu_n}\frac{dn(x)}{n(x)} = \frac{kT}{q}\frac{dn(x)}{n(x)} = -\frac{kT}{q}\frac{dp(x)}{p(x)}$$

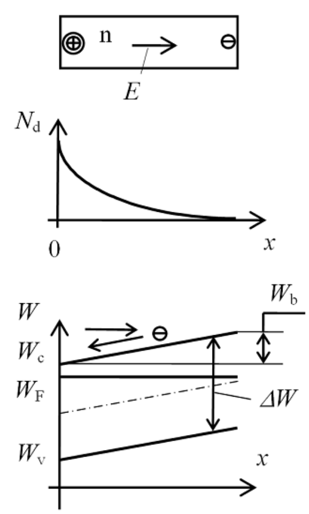
$$\int_{V_1}^{V_2} dV = \frac{kT}{q}\int_{n_1}^{n_2}\frac{dn(x)}{n(x)} = -\frac{kT}{q}\int_{p_1}^{p_2}\frac{dp(x)}{p(x)}$$

$$V_{21} = V_2 - V_1 = \frac{kT}{q}\ln\left(\frac{n_2}{n_1}\right) = -\frac{kT}{q}\ln\left(\frac{p_2}{p_1}\right)$$

Graded semiconductor

1. In equilibrium the Fermi level is constant.
2. The Fermi level in an intrinsic semiconductor is in the mid-gap position.
3. The Fermi level in the n-type semiconductor is over the middle of the forbidden band.
4. The Fermi level in the p-type semiconductor is below the middle of the forbidden band.

... **The potential barriers appear in graded semiconductors**.



$$W_{21} = W_2 - W_1 = -q\,V_{21} \qquad V_{21} = \varphi_2 - \varphi_1 = -W_{21}/q$$

Because in the graded n-type semiconductor the height of the potential barrier does not exceed ΔW, the built-in potential in a graded specimen satisfies the condition

$$|U_k| \le \frac{\Delta W}{2q} \qquad W = E_C \text{ or } E_F \text{ or } E_V$$

Mass Action Law

$$p_1 = p_2 \epsilon^{V_{21}/V_T} \qquad n_1 = n_2 \epsilon^{-V_{21}/V_T}$$

$$n_1 p_1 = n_2 p_2$$

$$n = p = n_i \qquad np = n_i^2$$

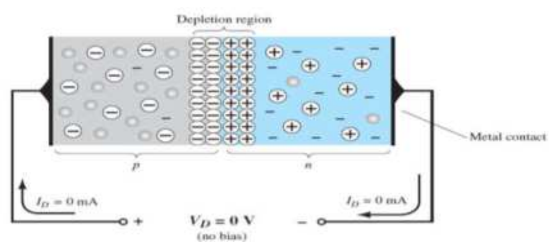
Open circuited Step Graded Junction

$$V_o = V_{21} = V_T \ln \frac{p_{po}}{p_{no}} \qquad p_{no} = n_i^2/N_D$$

$$V_o = V_T \ln \frac{N_A N_D}{n_i^2}$$

The PN-Junction, Formation of depletion region and Barrier potential

- The interface in-between p-type and n-type material is called a *pn-junction*.



The barrier potential $V_B \cong 0.6 - 0.7V$ for Si and $0.2 - 0.3V$ for Ge at 300K: as T ↑ , V_B ↓ .

The barrier potential decreases by approximately 2.5 mV/°C rise in temperature

OPEN CIRCUIT PN-JUNCTION

$$\frac{d^2V}{dx^2} = -\frac{\rho}{\varepsilon}$$

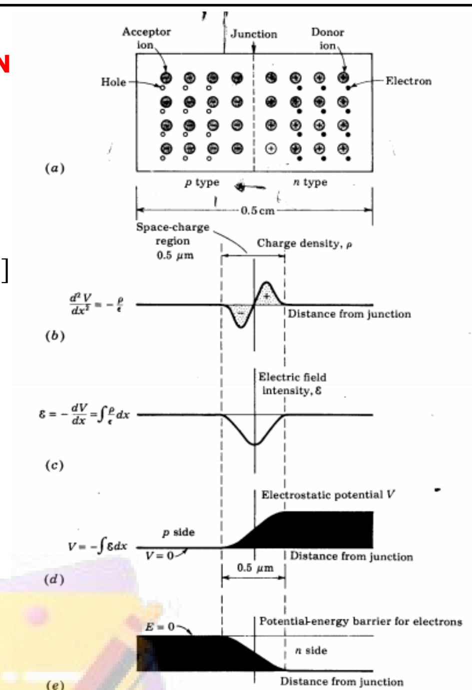
$[\rho - \text{chargedensity}, \varepsilon - \text{permittivity}]$

$\because E = -dV/dx$

$$-\frac{d^2V}{dx^2} = \frac{d}{dx}\left(-\frac{dV}{dx}\right) = \frac{\rho}{\varepsilon}$$

$$\Rightarrow E = \int_{x_o}^{x} \frac{\rho}{\varepsilon} dx \, [E = 0 @ x = x_o]$$

$$V = -\int E dx$$



The PN-Junction, Formation of depletion region and Barrier potential

- The interface in-between p-type and n-type material is called a ***pn-junction***.

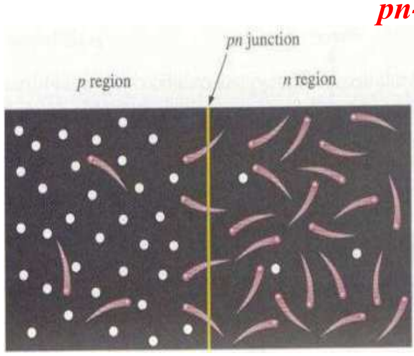


Fig. (a)

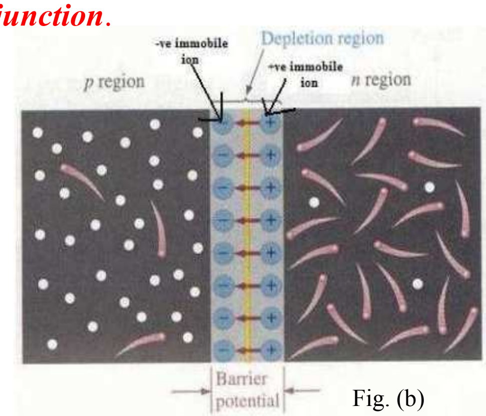


Fig. (b)

The barrier potential $V_B \cong 0.6 - 0.7V$ for Si and $0.2 - 0.3V$ for Ge at 300K : as T $\uparrow$, $V_B \downarrow$.

QUIZ

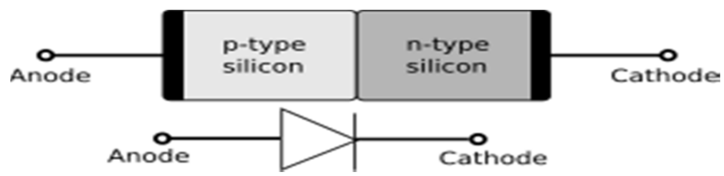
- The potential difference across the p-n junction is called…………
  (Barrier potential)
- The physical distance from one side to other side of depletion region is called……… of depletion region.
  (width)
- The barrier potential of silicon diode is about ……volts.
  (0.7)
- The barrier potential of Ge diode is about ……volts.
  (0.3)

RECAP

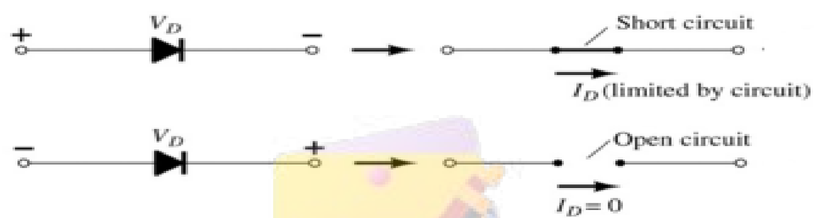
- **"Electronics Engineering"** is a field of science and engineering, which deals with electronic devices and their utilization.
- **"Electronic Device"** is the device in which conduction takes place by the movement of electrons through a vacuum, gas or a semiconductor (S/C).
- **"Valence Band"** The range of energies possessed by valence electrons.
- **"Conduction Band"** The range of energies possessed by free electrons.
- The three types of solids are: **1.** Insulator **2.** Semiconductor **3.** Conductor.
- **Intrinsic (pure) Semiconductor** means; which is in extremely pure form.
- **Doping:** adding of impurities **(dopants)** to the intrinsic semi-conductor material.
- **Extrinsic (impure) Semiconductor** means; which is in impure form.
- **P-type:** adding Group III dopant **(acceptor)** such as **B, Al, Ga, In.**
- **N-type:** adding Group V dopant **(donor)** such as **As, P, Sb, Bi.**
- The interface in-between p-type and n-type material is called a **pn-junction.**

Symbol of a p-n junction Diode

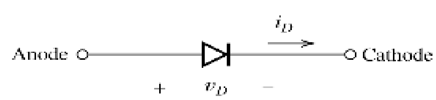
No movement of charge carriers through a p-n junction at equilibrium.



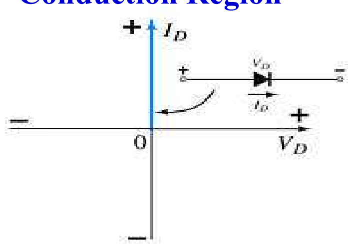
A diode ideally conducts in only one direction



Ideal Diode Characteristics

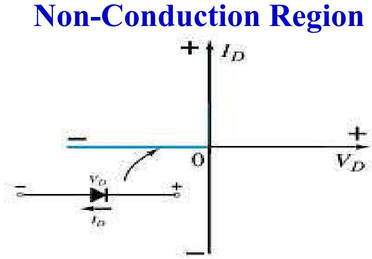


Conduction Region



- The voltage across the diode is 0V (means $V_B = 0$ V).
- Thus, the current is infinite.
- Now, diode acts like a short switch.

Non-Conduction Region

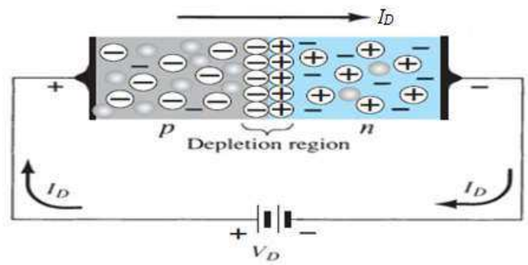


- All of the voltage is across the diode.
- Thus, the current is 0 A.
- The diode acts like open switch.

Diodes – Basic Diode Concepts

Biasing the PN-Junction

- **Forward Bias**: dc voltage positive terminal connected to the p region and negative to the n region. Here, V_{BIAS} (V_F) = V_B

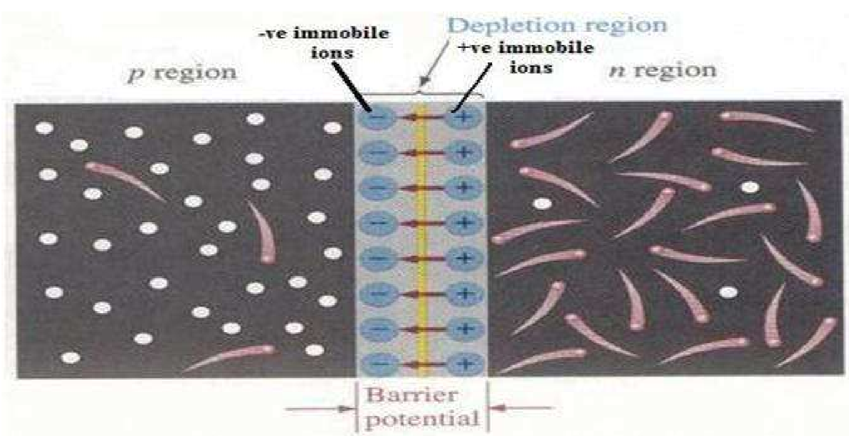


- **Knee Voltage:** The minimum forward voltage after which diode current increase exponential. Its value for Si is 0.7 V and for Ge is 0.3 V.

Diodes – Basic Diode Concepts

Biasing the PN-Junction

- **Forward Bias**: dc voltage positive terminal connected to the p region and negative to the n region. Here, V_{BIAS} (V_F) = V_B

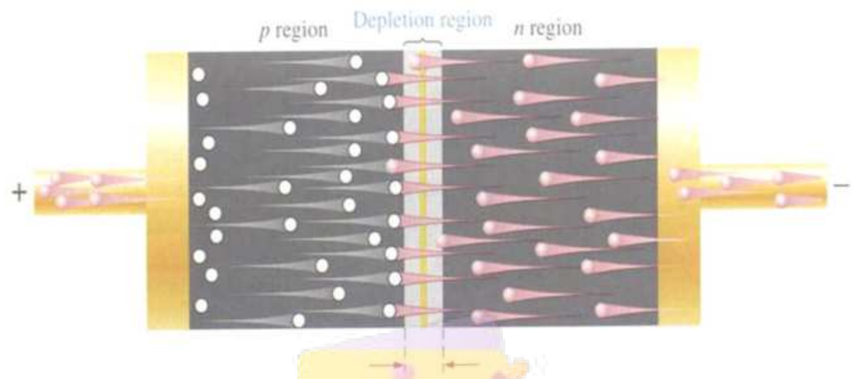


Biasing the PN-Junction

- **Forward Bias**: dc voltage positive terminal connected to the p region and negative to the n region.

if $V_{BIAS} (V_F) \geq V_B$

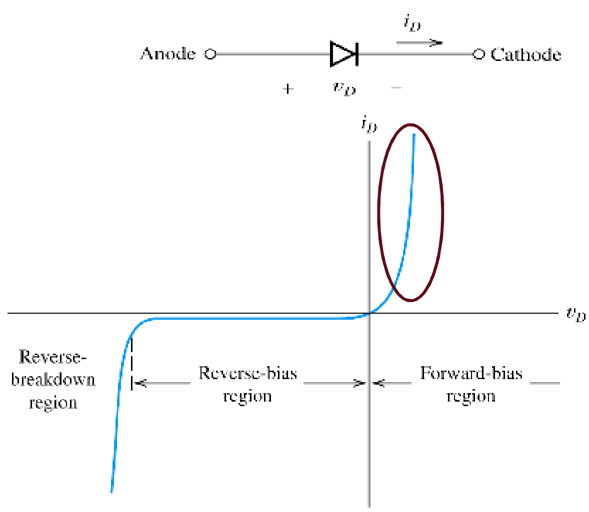
then width of depletion region decreases.



Diodes – Basic Diode Concepts

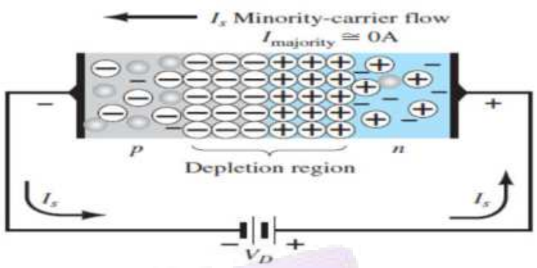
Biasing the PN-Junction

- **Forward Bias (practical V-I characteristics)**:



Diodes – Basic Diode Concepts

- **Reverse Bias**: dc voltage negative terminal connected to the p region and positive to the n region.
- Depletion region widens until its potential difference equals the bias voltage, majority-carrier current ceases.



Diodes – Basic Diode Concepts

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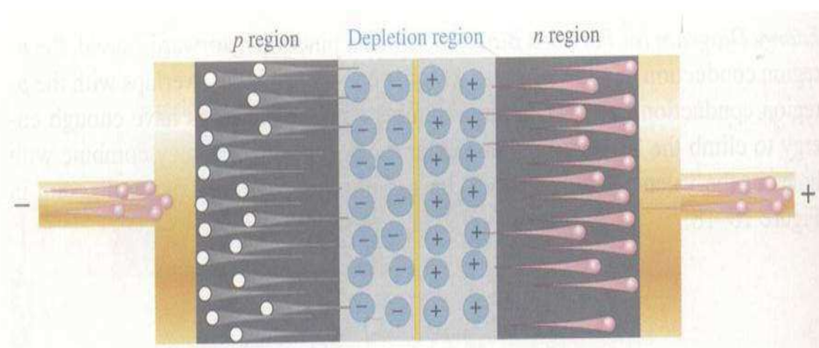
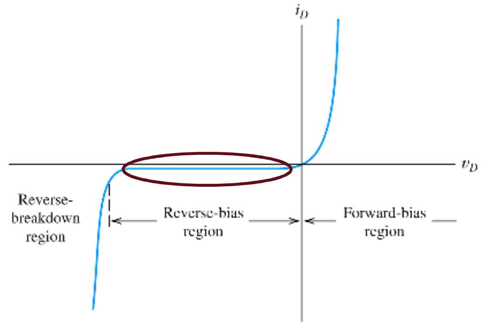
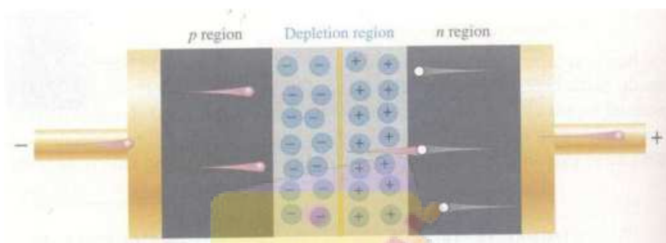


Diodes – Basic Diode Concepts

- **Reverse Bias (practical V-I characteristics)**:
  majority-carrier current ceases.



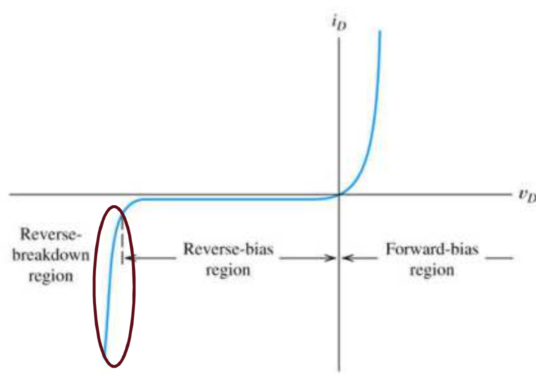
- However, there is still a very small current produced by minority carriers known as Reverse Saturation Current.



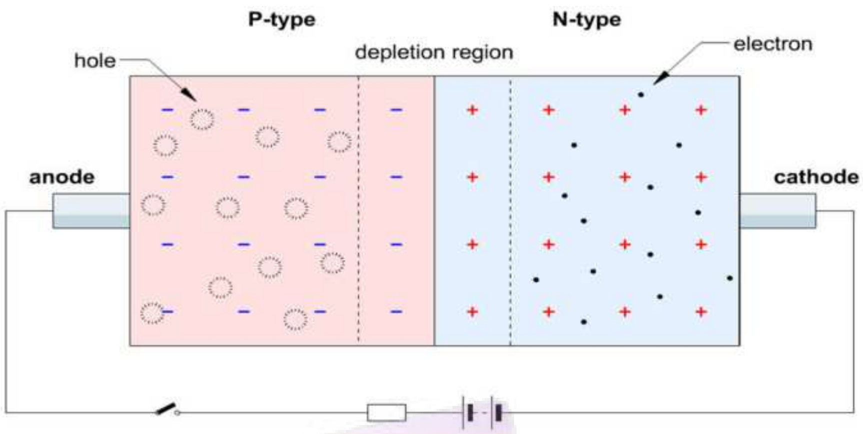
Diodes – Basic Diode Concepts

Biasing the PN-Junction

- **Reverse Breakdown:** As reverse voltage reach certain value, avalanche occurs and generates large current.



Biasing the PN-Junction (ANIMATION)



Diodes – Basic Diode Concepts

Diode current equation (Shockley Equation):

$$\boxed{I = I_O\left[\exp\left(\frac{v_D}{\eta V_T}\right) - 1\right]}$$

where $I_O \cong 10^{-14}$ A at 300K is the (reverse) saturation current,

$\eta \cong 1$ for Ge and 2 for Si where η = emission coefficient,

$V_T = \dfrac{kT}{q} \cong 0.026$V or 26mV at 300K is the thermal voltage

k is the Boltzman constant $= 1.38 \times 10^{-23}$ J/ °K or 8.62×10^{-5} eV/ °K,

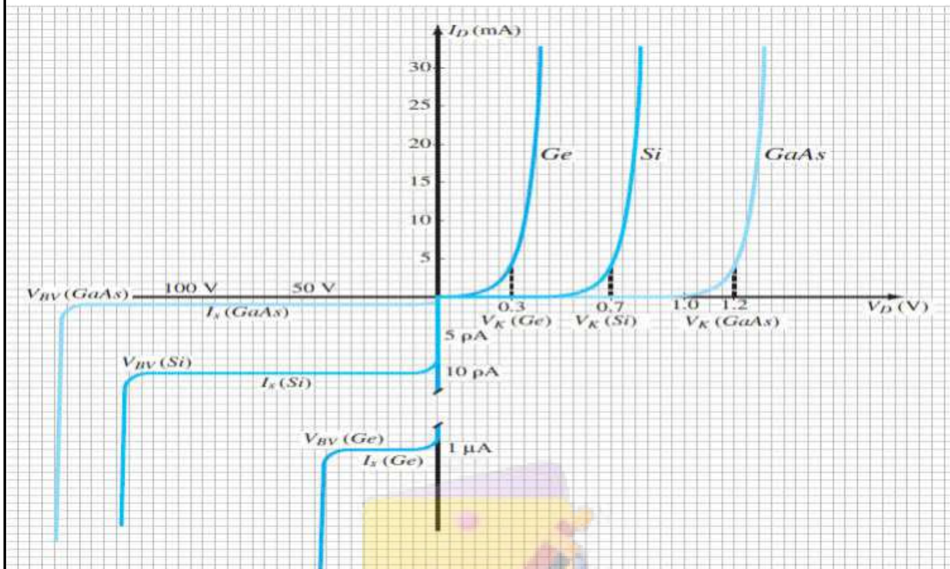
$q = 1.6 \times 10^{-19}$ C = electron charge

when Diode is FB then $\boxed{I \cong I_O\{\exp\left(\frac{v_F}{\eta V_T}\right) - 1\} \cong I_O \exp\left(\frac{v_F}{\eta V_T}\right)}$

when Diode is RB then, $\boxed{I \cong I_O\{\exp\left(\frac{-v_R}{\eta V_T}\right) - 1\} \cong -I_O}$

Diodes – Basic Diode Concepts

Comparison of Ge, Si & GaAs semiconductor PN-Junction diode



QUIZ

- The device having two electrodes is called………..
  (Diode)
- The arrowhead in the diode symbol points the direction of ……current.
  (Forward)
- Due to forward biasing, the depletion region …………….
  (Narrows)

RECAP

- Diode  ideally conducts in only one direction.
- In Forward Bias (FB), dc voltage positive terminal connected to the p region and negative to the n region.
- In Reverse Bias (RB), dc voltage negative terminal connected to the p region and positive to the n region.
- Ideal diode in FB acts like a short switch (zero resistance).
- Ideal diode in RB acts like a open switch (infinite resistance).
- Practically in RB there is still a very small current produced by minority carriers known as Reverse Saturation Current.
- If reverse voltage reach certain value, avalanche occurs and generates large current.
- Diode current equation is given as: $I = I_O\left[\exp\left(\frac{v_D}{\mathrm{n}\,V_T}\right) - 1\right]$

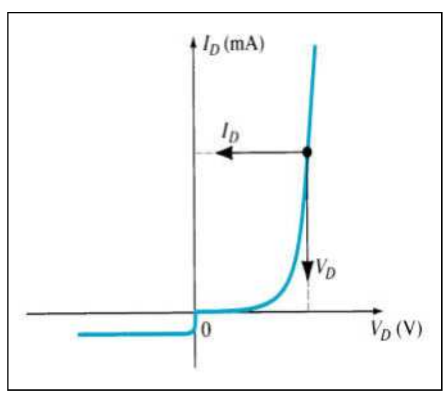
Diodes – Basic Diode Concepts

Diode Resistance: There are two type of resistance:

DC (Static) Resistance

- For a specific applied DC voltage (V_D) the diode has a specific current (I_D) and a specific resistance (R_D), is given as:

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



For FB $$R_F = \frac{V_F}{I_F}$$

For RB $$R_R = \frac{V_R}{I_R}$$

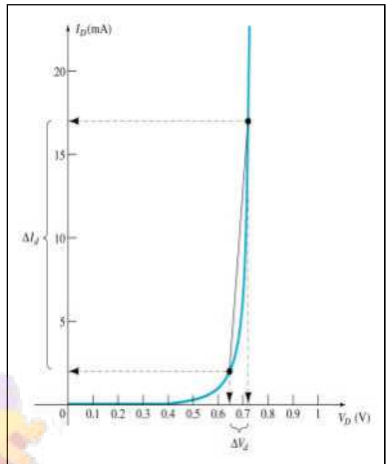
Diodes – Basic Diode Concepts

Diode Resistance:

AC (Dynamic) Resistance

AC resistance can be calculated using the current and voltage values for two points on the diode characteristic curve and is given as:

$$r_d = \frac{\Delta v_d}{\Delta i_d}$$



For FB: $$r_F = \frac{\Delta v_F}{\Delta i_F}$$

For RB: $$r_R = \frac{\Delta v_R}{\Delta i_R}$$

Dynamic resistance (r_d) from diode current equation

Shockley diode current equation is given by; $I_D = I_O\left(e^{\frac{V_D}{\eta V_T}} - 1\right)$ (1)

OR, $I_D = I_O e^{\frac{V_D}{\eta V_T}} - I_O$; OR $I_O e^{\frac{V_D}{\eta V_T}} = I_D + I_O$ (2)

Now differentiating equation no. 1 wrt V_D; we get

$$\frac{dI_D}{dV_D} = \frac{d}{dV_D}\left(I_O e^{\frac{V_D}{\eta V_T}} - I_O\right); \quad OR, \quad \frac{dI_D}{dV_D} = I_O e^{\frac{V_D}{\eta V_T}}\left(\frac{1}{\eta V_T}\right) - 0; \quad OR, \quad \frac{dI_D}{dV_D} = I_O e^{\frac{V_D}{\eta V_T}}\left(\frac{1}{\eta V_T}\right)$$

Now using equation no. 2 we get;

$$\frac{dI_D}{dV_D} = (I_D + I_O)\left(\frac{1}{\eta V_T}\right); \quad OR\ we\ can\ also\ write \quad \frac{dV_D}{dI_D} = \left(\frac{\eta V_T}{I_D + I_O}\right)$$

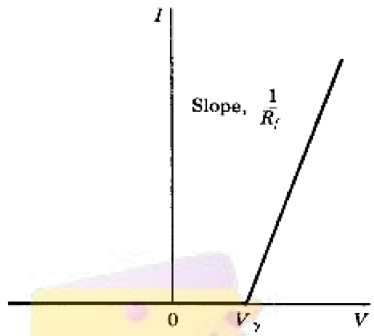
Since; $\frac{dV_D}{dI_D} = r_d$ and $I_D \gg I_O$

Therefore, $r_d \cong \left(\frac{\eta V_T}{I_D}\right)$

Where $\eta = 1$ (for Ge) and $\eta = 2$ (for Si) and $V_T = \frac{T\,(oK)}{11600}$ (in V)

Piecewise Linear Diode Characteristics

Break point is not at the origin, hence V_γ is called offset, or threshold voltage, or cut-in voltage. The diode behaves as open circuit if $V < V_\gamma$, and has a constant incremental resistance $r = dV/dI$ if $V > V_\gamma$. This resistance r is also called as forward resistance (R_f).



Examples

Example 1: Calculate the dynamic forward and reverse resistance of pn junction diode when the applied voltage is 0.5 V at temperature of 120 degree Celsius and reverse saturation current of 5 μA.

Solution: Given, $V_D = 0.5$ V, $I_o = 5$ μA, T = 120°C

Since,

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

Here we consider pn junction diode is made up of Si material (η=2).

$$V_T = \frac{T}{11600} = \frac{273 + 120}{11600} = 0.033879310\ V$$

Now for FB V_D = + 0.5 V,

$$I_D = I_O\left(e^{\frac{V_D}{\eta V_T}} - 1\right) = 5 \times 10^{-6}\left(e^{\frac{0.5}{2 \times 0.033879310}} - 1\right) = 5 \times 10^{-6}(e^{7.379137113} - 1)$$

$$= 5 \times 10^{-6}(1601.206648) = 8006.033241 \times 10^{-6}\ A = 8006.033241\ \mu A$$

Hence dynamic forward resistance;

$$r_d \cong \left(\frac{\eta V_T}{I_D + I_O}\right);\ \ r_d \cong \left(\frac{2 \times 0.033879310}{8006.033241\ \mu A + 5\mu A}\right) = 8.458162382\ \Omega = 8.46\ \Omega$$

Now for RB V_D = - 0.5 V,

$$I_D = I_O\left(e^{\frac{V_D}{\eta V_T}} - 1\right) = 5 \times 10^{-6}\left(e^{\frac{-0.5}{2 \times 0.033879310}} - 1\right) = 5 \times 10^{-6}(e^{-7.379137113} - 1)$$

$$= 5 \times 10^{-6}(-0.999375861) = -4.996879304 \times 10^{-6} = -4.996879304\ \mu A$$

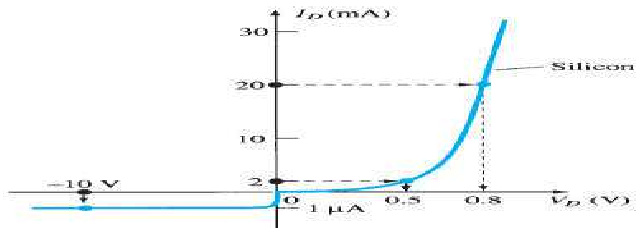
Hence dynamic reverse resistance;

$$r_d \cong \left(\frac{\eta V_T}{I_D + I_O}\right);\ \ r_d \cong \left(\frac{2 \times 0.033879310}{4.996879304\ \mu A + 5\mu A}\right) = 6777.977201\ \Omega = 6.777977201\ k = 6.78\ k\Omega$$

Examples

Example: 2 Determine the dc resistance levels for the diode shown in fig.

a. $I_D = 2$ mA (low level)
b. $I_D = 20$ mA (high level)
c. $V_D = -10$ V (reverse-biased)



Solution:

(a) At $I_D = 2$ mA, $V_D = 0.5$ V (from the curve) and

$$R_D = \frac{V_D}{I_D} = \frac{0.5\text{ V}}{2\text{ mA}} = \mathbf{250\ \Omega}$$

(b) At $I_D = 20$ mA, $V_D = 0.8$ V (from the curve) and

$$R_D = \frac{V_D}{I_D} = \frac{0.8\text{ V}}{20\text{ mA}} = \mathbf{40\ \Omega}$$

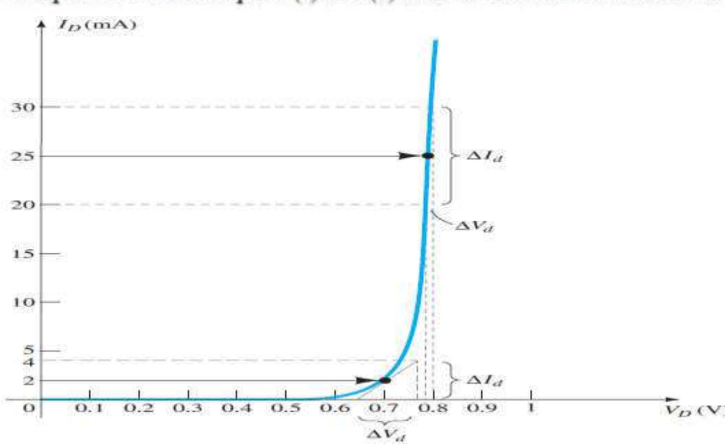
(c) At $V_D = -10$ V, $I_D = -I_s = -1\ \mu$A (from the curve) and

$$R_D = \frac{V_D}{I_D} = \frac{10\text{ V}}{1\ \mu\text{A}} = \mathbf{10\ M\Omega}$$

Examples

Example: 3 For the characteristics of fig.

(a) Determine the ac resistance at $I_D = 2$ mA.
(b) Determine the ac resistance at $I_D = 25$ mA.
(c) Compare the results of parts (a) and (b) to the dc resistances at each current level.



Solution:

(a) For $I_D = 2$ mA: the tangent line at $I_D = 2$ mA was drawn as shown in the figure and a swing of 2 mA above and below the specified diode current was chosen. At $I_D = 4$ mA, $V_D = 0.76$ V, and at $I_D = 0$ mA, $V_D = 0.65$ V. The resulting changes in current and voltage are

$$\Delta I_d = 4 \text{ mA} - 0 \text{ mA} = 4 \text{ mA}$$

and

$$\Delta V_d = 0.76 \text{ V} - 0.65 \text{ V} = 0.11 \text{ V}$$

and the ac resistance:

$$r_d = \frac{\Delta V_d}{\Delta I_d} = \frac{0.11 \text{ V}}{4 \text{ mA}} = \mathbf{27.5\ \Omega}$$

(b) For $I_D = 25$ mA, the tangent line at $I_D = 25$ mA was drawn as shown on the figure and a swing of 5 mA above and below the specified diode current was chosen. At $I_D = 30$ mA, $V_D = 0.8$ V, and at $I_D = 20$ mA, $V_D = 0.78$ V. The resulting changes in current and voltage are

$$\Delta I_d = 30 \text{ mA} - 20 \text{ mA} = 10 \text{ mA}$$

and

$$\Delta V_d = 0.8 \text{ V} - 0.78 \text{ V} = 0.02 \text{ V}$$

and the ac resistance is

$$r_d = \frac{\Delta V_d}{\Delta I_d} = \frac{0.02 \text{ V}}{10 \text{ mA}} = \mathbf{2\ \Omega}$$

c. For $I_D = 2$ mA, $V_D = 0.7$ V and

$$R_D = \frac{V_D}{I_D} = \frac{0.7 \text{ V}}{2 \text{ mA}} = 350\ \Omega$$

which far exceeds the r_d of 27.5 Ω.

For $I_D = 25$ mA, $V_D = 0.79$ V and

$$R_D = \frac{V_D}{I_D} = \frac{0.79 \text{ V}}{25 \text{ mA}} = 31.62\ \Omega$$

which far exceeds the r_d of 2 Ω.

QUIZ

- An ideal diode in the conducting and non conducting states are equivalent to ……….. and ……..… switch respectively .

  (Close , Open)

- The reverse saturation current ……… for every 10^0C rise in temperature.

  (Doubles)

- The reverse saturation current is flow due to………..

  (Minority Carriers)

Diode Capacitances

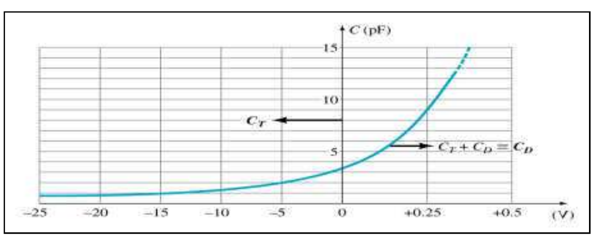
Diode Capacitance: Capacitance offered by diode is diode capacitance.

- In **forward biased**, **Storage Capacitance Or Diffusion Capacitance (C_D)** exists. It is given as:

$$C_D = \frac{\tau I_D}{\eta V_T}$$

- In **reverse biased**, **Depletion Or Transition Capacitance (C_T)** exists. It is given as:

$$C_T = \frac{\varepsilon A}{W}$$



Diode Capacitances: Transition capacitance, C_T

$$C_T = \left|\frac{dQ}{dV}\right|$$

A change in voltage dV in a time dt will result in a current, i

$$i = \frac{dQ}{dt} = C_T \frac{dV}{dt}$$

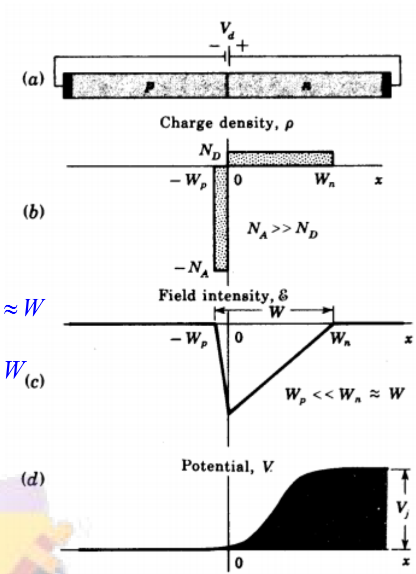
For Step Graded Junction

$$N_A W_p = N_D W_n \qquad \text{If } N_A \gg N_D \Rightarrow W_p \ll W_n \approx W$$

$$\frac{d^2V}{dx^2} = \frac{-qN_D}{\varepsilon}; \qquad E = -\frac{dV}{dx} = 0 @ x = W_n \approx W$$

$$\frac{dV}{dx} = \frac{-qN_D}{\varepsilon}(x - W) = -E;$$

Neglecting potential drop across W_p, we arbitrarily choose $V=0$ @ $x=0$.



Diode Capacitances: Transition capacitance, C_T

Neglecting potential drop across W_p, we arbitrarily choose $V=0$ @ $x=0$ and Integrating

$$\frac{dV}{dx} = \frac{-qN_D}{\varepsilon}(x - W) = -E \Rightarrow V = \frac{-qN_D}{\varepsilon}(x^2 - 2Wx)$$

At $x=W$, $V=Vj$ = Junction or barrier potential. Thus,

$$V_j = \frac{qN_D W^2}{2\varepsilon} \qquad W = \sqrt{\frac{2\varepsilon V_j}{qN_D}}$$

Since, Junction or barrier potential represents reverse voltage, it is lowered by an applied forward voltage.

$$V_j = V_o - V_d$$

Depletion layer thickness increases with applied reverse voltage

$$W \propto \sqrt{V_j} = \sqrt{(V_o - V_d)}$$

Diode Capacitances: Transition capacitance, C_T

If A is the area of the junction, charge in distance W is

$$Q = qN_D WA$$

The transition capacitance, C_T is given by

$$W \propto \sqrt{V_j} = \sqrt{(V_o - V_d)}$$

$$C_T = \left|\frac{dQ}{dV_d}\right| = qN_D A\left|\frac{dW}{dV_j}\right|$$

$$\left|\frac{dW}{dV_j}\right| = \frac{\varepsilon}{qN_D W}$$

$$C_T = \frac{\varepsilon A}{W}$$

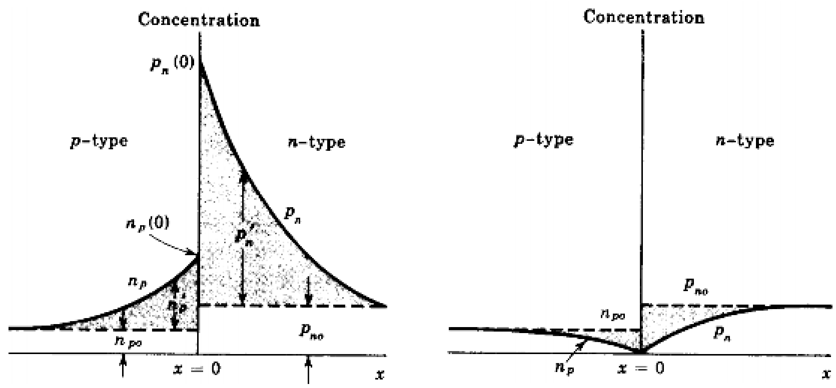
If the concentration, NA is not negligible, then we replace

$$\frac{1}{N_D} \Rightarrow \left(\frac{1}{N_A} + \frac{1}{N_D}\right)$$

$$W = \sqrt{\frac{2\varepsilon V_j}{qN_D}} = \sqrt{\frac{2\varepsilon V_j}{q}\left(\frac{1}{N_D}\right)}$$

Diffusion capacitance, C_D

In forward bias, potential barrier at Junction is lowered: holes (p -> n) & electrons (n -> p)



$$p_n' = p_n - p_{n0}$$

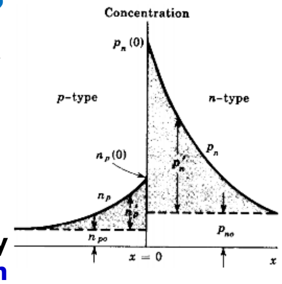
$$n_p' = n_p - n_{p0}$$

Minority Injection

Diffusion capacitance, C_D

Assume one side of diode is so heavily doped (say p-side) in comparison to n-side, that the current I carried across the junction is entirely due to holes moving from p to n side.

$$I = I_{pn}(0)$$



The excess minority charge Q exists only on n-side, and is given by shaded area in n-region multiplied by cross section A and the unit charge q.

$$Q = \int_0^\infty Aqp'(0)e^{-x/L_p}dx = AqL_p p'(0)$$

The hole current I is given by

$$I = \frac{AqD_p p'(0)}{L_p}$$

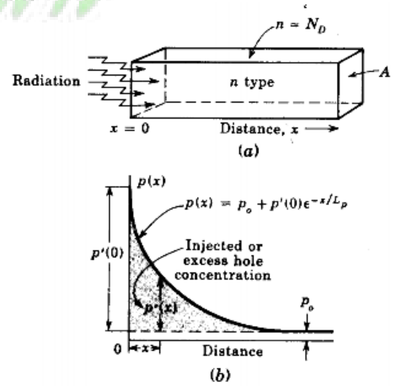
$$p'(x) = p'(0)e^{-x/L_p} = p(x) - p_0 \qquad \left[\because @ x = 0 \Rightarrow p'(0) = p(0) - p_0\right]$$

$$I_p = AJ_p = -AqD_p\frac{dp}{dx} = -AqD_p p'(0)\left(-\frac{1}{L_p}e^{-x/L_p}\right)$$

$$= \frac{AqD_p}{L_p}\left[p(0) - p_0\right]e^{-x/L_p}$$

Diffusion capacitance, C_D

Assume one side of diode is so heavily doped (say p-side) in comparison to n-side, that the current I carried across the junction is entirely due to holes moving from p to n side.



$$\frac{d^2p}{dx^2} = \frac{p - p_0}{D_p\tau_p} \qquad \left[Lp \equiv \sqrt{D_p\tau_p}\right]$$

$$p'(x) = p'(0)e^{-x/L_p} = p(x) - p_0 \qquad \left[\because @ x = 0 \Rightarrow p'(0) = p(0) - p_0\right]$$

$$I_p = AJ_p = -AqD_p\frac{dp}{dx} = -AqD_p p'(0)\left(-\frac{1}{L_p}e^{-x/L_p}\right)$$

$$= \frac{AqD_p}{L_p}\left[p(0) - p_0\right]e^{-x/L_p}$$

QUIZ

- The C_T and C_D exists in ………..and……….bias.

  (Reverse , Forward)

- The resistance of a diode under dc conditions is called …………….. resistance .

  (Static)

- The reciprocal of the slope of the forward characteristics is called………………

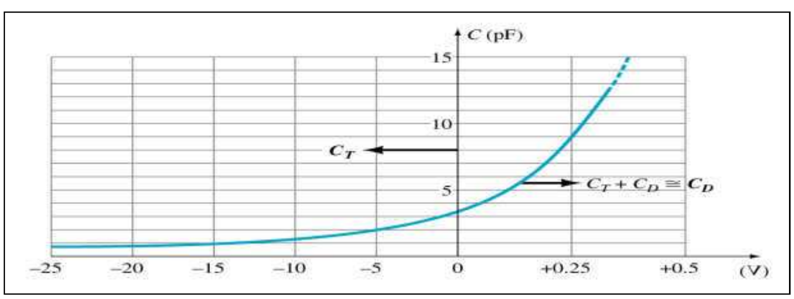
  (Dynamic Resistance)

RECAP

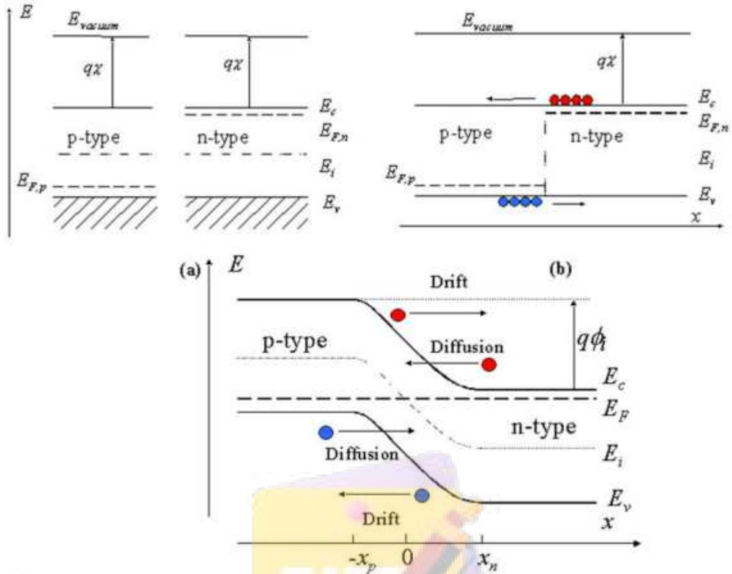
- There are two types of diode capacitance:

1. Storage Capacitance **OR** Diffusion Capacitance (C_D) ⟹ in FB
2. Depletion Or Transition Capacitance (C_T) ⟹ in RB

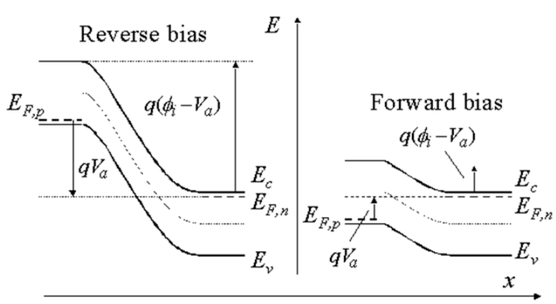
- Formulas are given as: $C_D = \frac{\tau I_D}{\eta V_T}$ $C_T = \frac{\xi A}{W}$



p-n Junction Energy Band Diagram

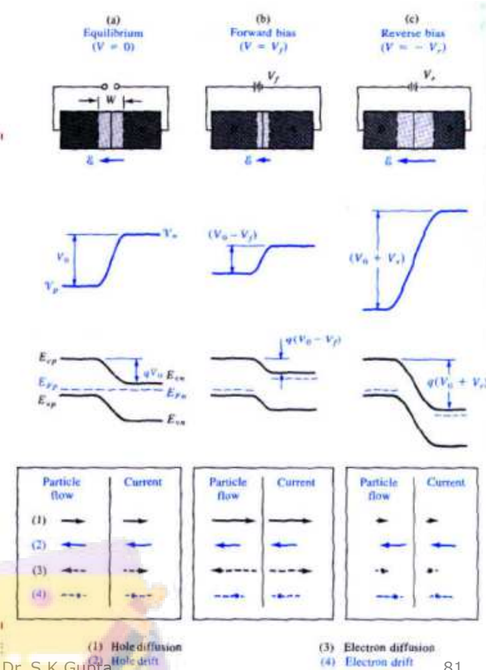


p-n Junction Energy Band Diagram



Animation pn junction formation
{https://www.doitpoms.ac.uk/tlplib/semiconductors/pn.php}

Review of Biasing



- Applying a bias adds or subtracts to the built-in potential.
- This changes the diffusion current, making it harder or easier for the carriers to diffuse across.
- The drift current is essentially constant, as it is dependent on temperature.

Special Diodes

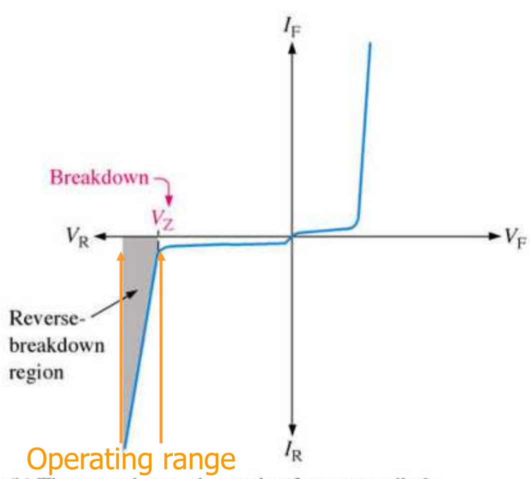
- Zener Diode
- LEDs
- Photo Diode
- Varactor Diode
- Tunnel Diode
- Schottky Diode
- Schokley Diode

Zener Diode

- A **Zener diode** is a type of diode that permits current not only in the forward direction like a normal diode, but also in the reverse direction if the voltage is larger than the breakdown voltage known as "Zener knee voltage" or "Zener voltage". The device was named after Clarence Zener, who discovered this electrical property
- It is heavily doped in comparison with normal diode to reduce the breakdown voltage.
- Breakdown voltage for commonly available zener diodes can vary widely from 1.2 volts to 200 volts.

Zener Diodes – Operating Range

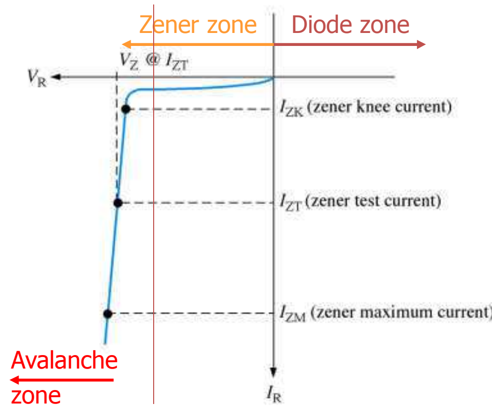
A zener diode is much like a normal diode, the exception being is that it is placed in the circuit in reverse bias and operates in reverse breakdown. This typical characteristic curve illustrates the operating range for a zener. Note that its forward characteristics are just like a normal diode.



(b) The normal operating region for a zener diode is shaded.

Zener Diodes – Regulation Ranges

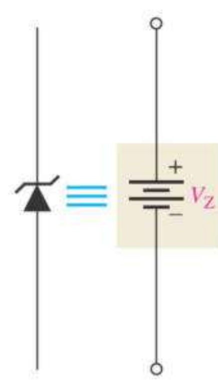
The zener diode's breakdown characteristics are determined by the doping process. Low voltage zeners (>5V), operate in the zener breakdown range. Those designed to operate <5 V operate mostly in avalanche breakdown range. Zeners are available with voltage breakdowns of 1.8 V to 200 V.



This curve illustrates the minimum and maximum ranges of current operation that the zener can effectively maintain its voltage.

Zener Diodes – Equivalent Circuit

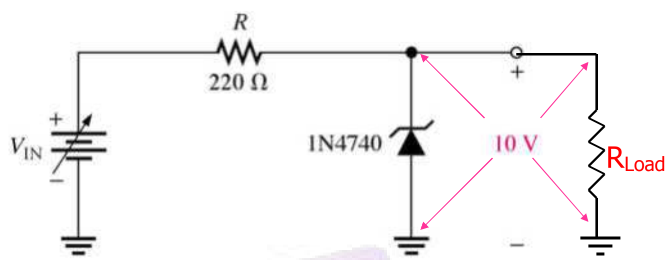
- Ideal Zener exhibits a constant voltage, regardless of current drawn.
- Ideal Zener exhibits no resistance characteristics.



(a) Ideal

Introduction

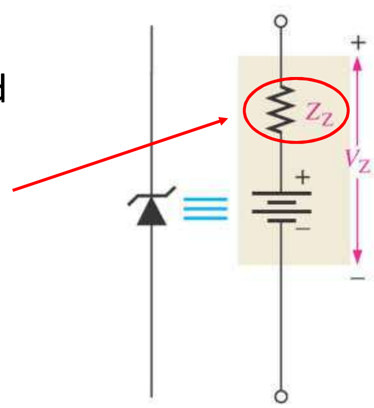
The basic function of **zener diode** is to maintain a specific voltage across its terminals within given limits of line or load change. Typically it is used for providing a stable reference voltage for use in power supplies and other equipment.



This particular zener circuit will work to maintain 10 V across the load.

Zener Diodes – Equivalent Circuit

- Zener exhibits a near constant voltage, varied by current drawn through the series resistance Z_Z.
- As Iz increases, Vz also increases.



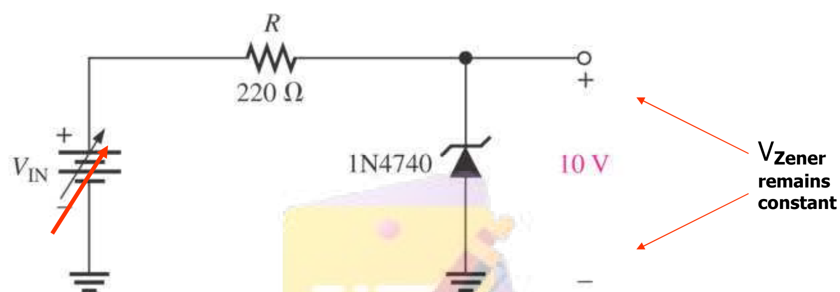
(b) Practical

Zener Diode - Applications

Regulation

In this simple illustration of zener regulation circuit, the zener diode will "adjust" its impedance based on varying input voltages. Zener current will increase or decrease directly with voltage input changes. The zener current, Iz, will vary to maintain a constant Vz.

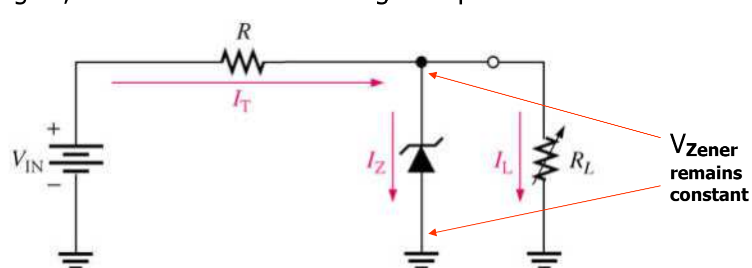
Note: The zener has a finite range of current operation.



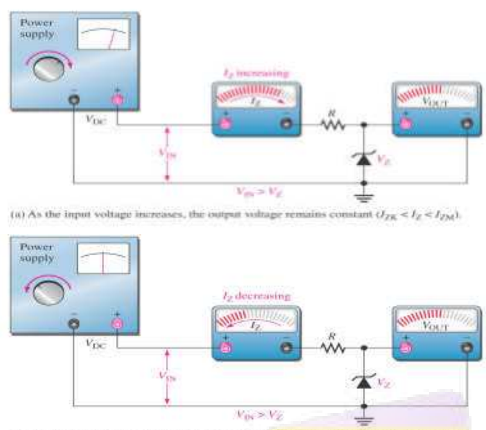
Zener Diode - Applications

Regulation

In this simple illustration of zener regulation circuit, the zener diode will "adjust" its impedance based on varying input voltages and loads (R_L) to be able to maintain its designated zener voltage. Zener current will increase or decrease directly with voltage input changes. The zener current will increase or decrease inversely with varying loads. Again, the zener has a finite range of operation.



Zener Diode - Applications



(a) As the input voltage increases, the output voltage remains constant ($I_{ZK} < I_Z < I_{ZM}$).

(b) As the input voltage decreases, the output voltage remains constant ($I_{ZK} < I_Z < I_{ZM}$).

Vin ↑ I_Z ↑ Vout →

Vin ↓ I_Z ↓ Vout →

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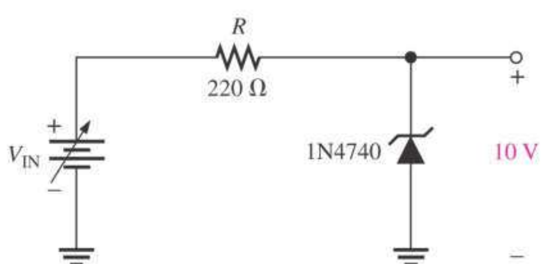
Zener Diode - Applications



1N4740

P_{DMAX} = 1W. V_Z = 10V.

I_{ZK} = 0.25mA to I_{ZM} = 100mA

V_{Rmin} = $I_{ZK}R$= .25mA x 220 = 55mV

V_{Rmax} = I_{ZM} = 100mA x 220 = 22V.

Acrobat Document

Calculate $V_{ZRegulate}$: (pg.118)

$V_{in_{MIN}}$ = V_R + V_Z = 55mV + 10V = 10.055V.

V_R = I_ZR = (100mA)(220) = 22V.

$V_{in(max)}$ = 22V + 10V = 32V

∴ V_{Reg} is ≈10V to 32V.

See Ex. 3-5

See Ex. 3-6

See Ex. 3-7

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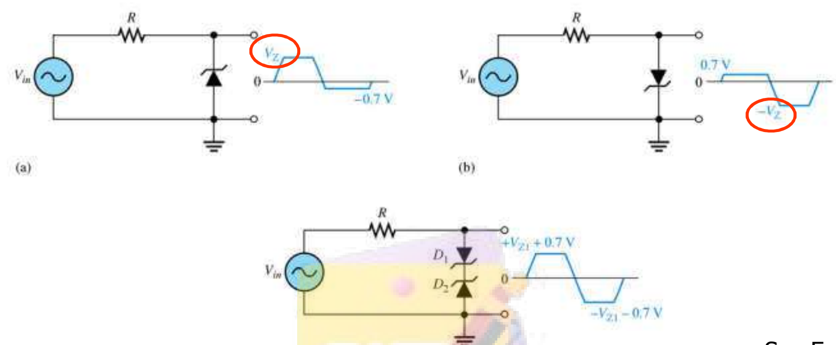
Zener Limiting

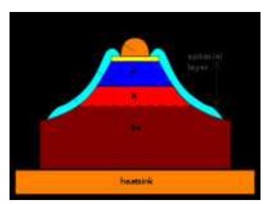
Zener diodes can be used for limiting just as normal diodes. The difference to consider for a Zener limiter is its zener breakdown characteristics.



See Ex.3-8

Varactor Diode

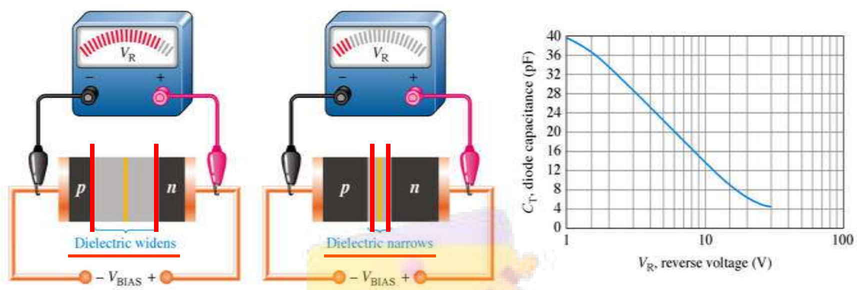
- A junction diode which act as a variable capacitor under changing reverse bias is known as a varactor diode.



$$C = \varepsilon_r \frac{A}{4\pi d}$$

Varactor Diodes

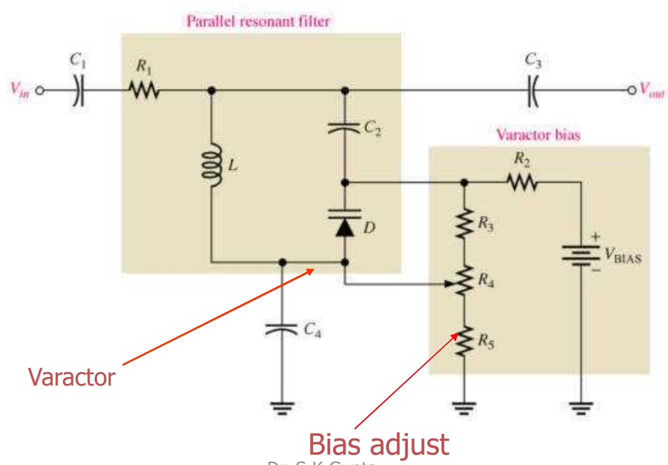
A **varactor diode** is best explained as a variable capacitor. Think of the depletion region as a variable dielectric. The diode is placed in reverse bias. The dielectric is "adjusted" by reverse bias voltage changes.



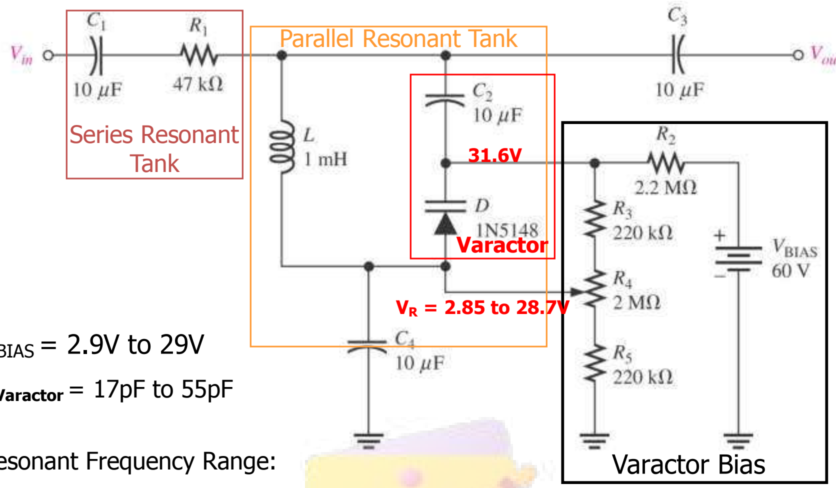
(a) Greater reverse bias, less capacitance (b) Less reverse bias, greater capacitance (c) Graph of diode capacitance versus reverse voltage

Varactor Diodes

The varactor diode can be useful in filter circuits as the adjustable component for resonance frequency selection.



Resonant Band-pass Filter w/ Varactor Diode



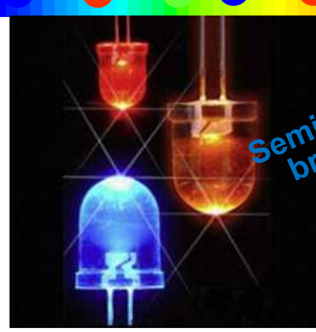
V_{BIAS} = 2.9V to 29V

$C_{Varactor}$ = 17pF to 55pF

Resonant Frequency Range:

f_r = 679kHz to 1.22MHz.

What is LED?

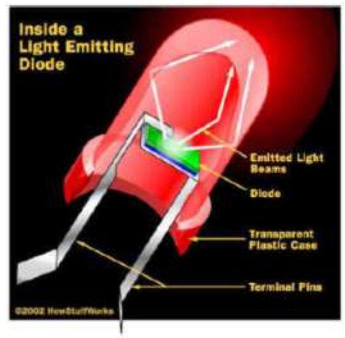


Semiconductors bring quality to light!

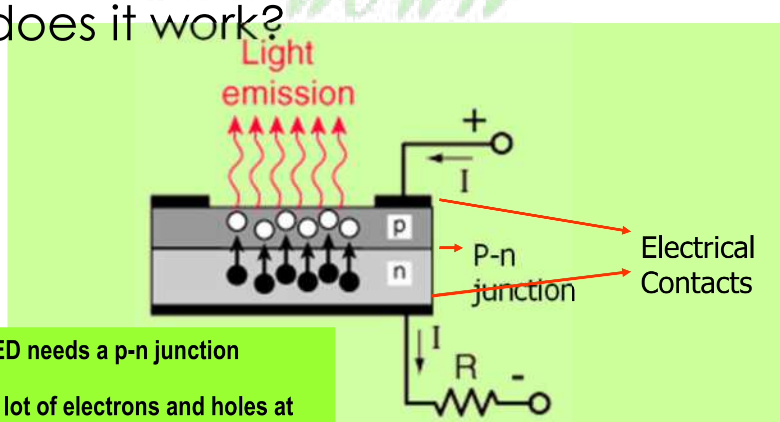
LEDs are semiconductor p-n junctions that under forward bias conditions can emit radiation by electroluminescence in the UV, visible or infrared regions of the electromagnetic spectrum. The qaunta of light energy released is approximately proportional to the band gap of the semiconductor.

Light Emitting Diodes

- When electrons and holes combine, they release energy.
- This energy is often released as heat into the lattice, but in some materials, known as *direct bandgap* materials, they release light.
- Engineering LEDs can be difficult, but has been done over a wide range of wavelengths.
- This illustration describes the importance of the plastic bubble in directing the light so that it is more effectively seen.



How does it work?



A typical LED needs a p-n junction

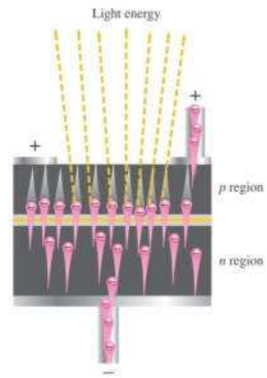
There are a lot of electrons and holes at the junction due to excitations

Electrons from n need to be injected to p to promote recombination

Junction is biased to produce even more e-h and to inject electrons from n to p for recombination to happen

Recombination produces light!!

Optical Diode



Electroluminescence, the process of emitting photons from a parent material (substrate), is the basis for LEDs.

Colors result from the choice of substrate material and the resulting *wavelength*;

Todays LEDs (green,red, yellow) are based on *indium gallium aluminum phosphide*

Blue uses *silicon carbide or gallium nitride*

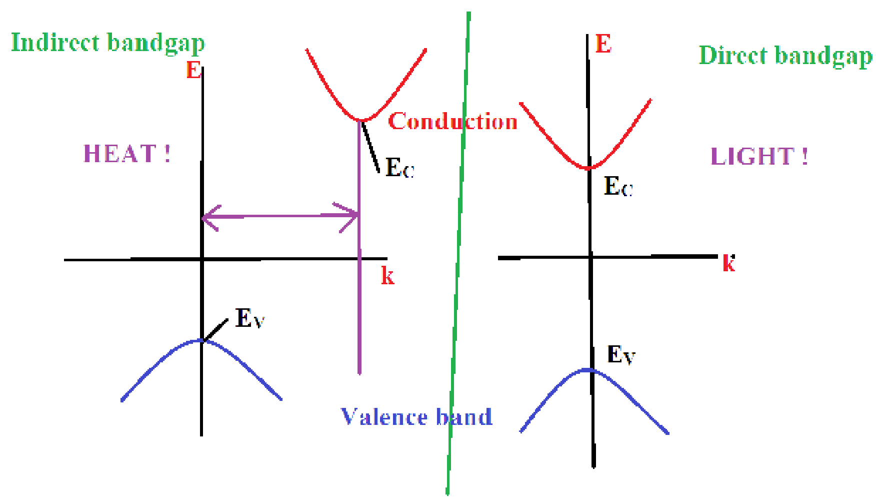
IR (infrared) – GaAs (gallium arsenide)

LED Biasing: 1.2V to 3.2V is typical.

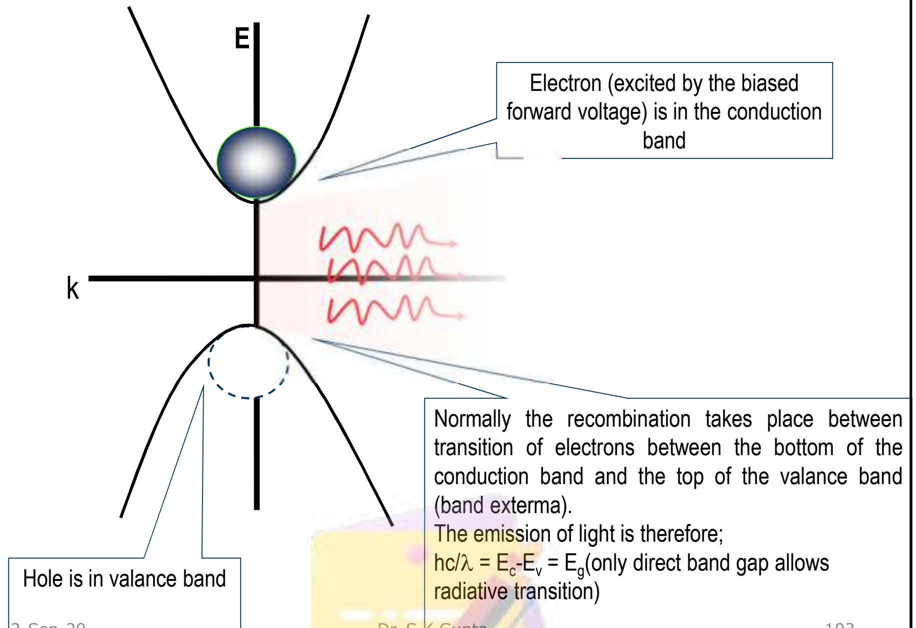
Note: Some newer LED's run at higher voltages and emit immense light energy.

Applications: Traffic signals
Outdoor video screens
Runway markers

A strong +bias encourages conduction-band electrons in the N-material to leap the junction and recombine with available holes releasing light and heat.

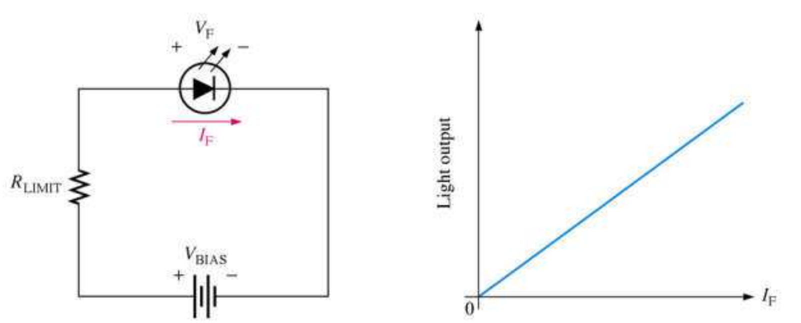


Excitation



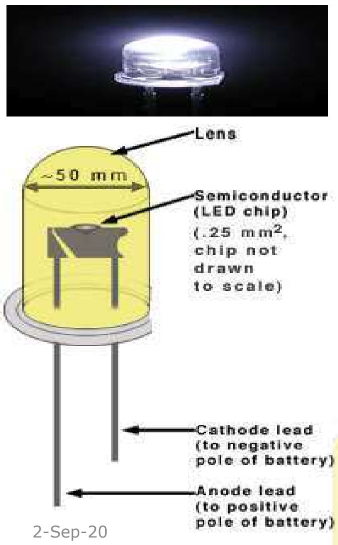
Optical Diodes

The light-emitting diode (LED) emits photons as visible light. Its purpose is for indication and other intelligible displays. Various impurities are added during the doping process to vary the color output.



(a) Forward-biased operation (b) General light output versus forward current

Getting to know LED



Advantages of Light Emitting Diodes (LEDs)

Longevity:

The light emitting element in a diode is a small conductor chip rather than a filament which greatly extends the diode's life in comparison to an incandescent bulb (10 000 hours life time compared to ~1000 hours for incandescence light bulb)

Efficiency:

Diodes emit almost no heat and run at very low amperes.

Greater Light Intensity:

Since each diode emits its own light

Cost:

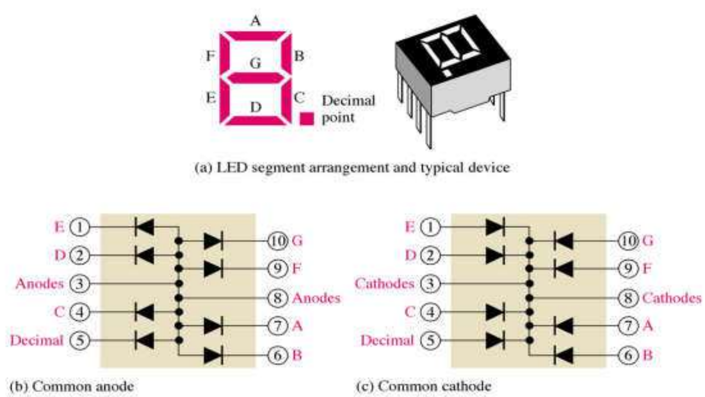
Not too bad

Robustness:

Solid state component, not as fragile as incandescence light bulb

Applications of LEDs

The seven segment display is an example of LEDs use for display of decimal digits.



(a) LED segment arrangement and typical device

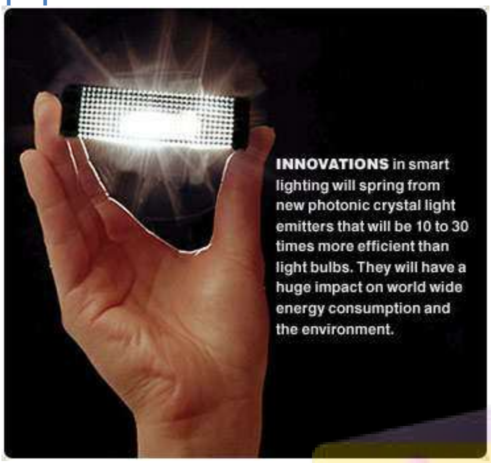
(b) Common anode

(c) Common cathode

Acrobat Document

See "Light Emitting Diodes.pdf"

Applications of LEDs



Definition:
LED which could emit visible light, the band gap of the materials that we use must be in the region of visible wavelength = 390- 770nm. This coincides with the energy value of 3.18eV- 1.61eV which corresponds to colours as stated below:

Colour of an LED should emits

Violet	***~ 3.1***
Blue	***~ 2.73eV***
Green	***~ 2.52eV***
Yellow	***~ 2.15eV***
Orange	***~ 2.08eV***
Red	***~ 1.62eV***

The band gap, E_g that the semiconductor must posses to emit each light

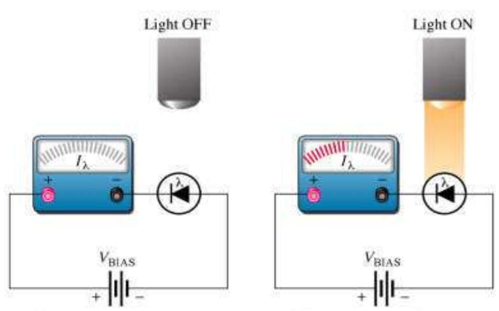
PHOTODIODES

- Photodiodes - a semiconductor p-n junction device whose region of operation is limited to the reversed bias region. Converts non-electrical energy such as light to electrical energy.
- Photons - energy transmitted as discrete packages,has a level directly related to the frequency of the travelling wave. This energy associated with incident light waves is directly related to the frequency of the travelling wave.
- Dark current - current that will exist with no applied illumination.
- Conductivity of semi-conductor is increased.
- Current flow in the semi-conductor is induced.

Photodiodes

Unlike LED's, photodiodes receive light rather than produce light. The photodiode varies it's current in response to the amount of light that strikes it. It is placed in the circuit in reverse bias. As with most diodes, no current flows when in reverse bias, but when light strikes the exposed junction through a tiny window, reverse current increases proportional to light intensity (irradiance).

Note: Photodiodes all exhibit a "reverse leakage current" which appears as an inverse variable resistance. Irradiance causes the device to exhibit a reduction in the variable resistance characteristic.



(a) No light, no current except negligible dark current

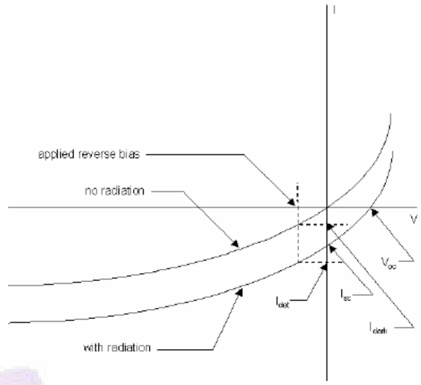
(b) Where there is incident light, resistance decreases and there is reverse current.

Photodiodes

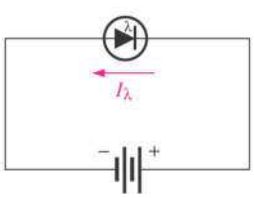
•Diodes have an optical generation rate. Carriers are created by shining light with photon energy greater than the bandgap.

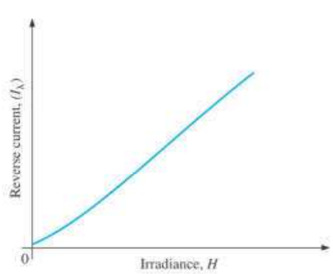
•Photodetector: should have large depletion widths and long diffusion lengths (minority carrier lifetimes) so that photo generatedEHPscan be collected and swept across the junction.

•Solar Cell: operating in the fourth quadrant generates current, though small.

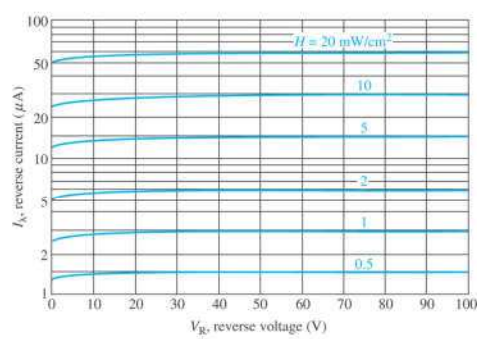


Photodiodes





(a) General graph of reverse current versus irradiance

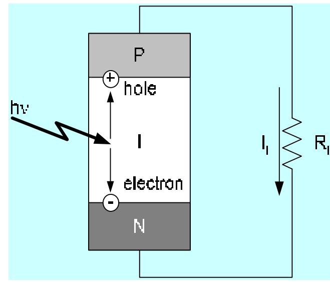


(b) Example of a graph of reverse current versus reverse voltage for several values of irradiance

Photodiode fundamentals

Based on PN or PIN junction diode

photon absorption in the depletion region induces current flow



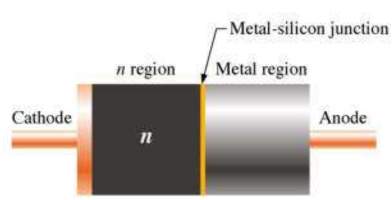
Spectral sensitivity

Material	Band gap (eV)	Spectral sensitivity
silicon (Si)	1.12	250 to 1100 nm
indium arsenide (InGaAs)	~0.35	1000 to 2200 nm
Germanium (Ge)	.67	900 to 1600 nm

Schottky Diode

The Schottky diode's (hot-carrier diodes) significant characteristic is its fast switching speed. This is useful for high frequencies and digital applications. It is not a typical diode in that it does not have a p-n junction. Instead, it consists of a lightly-doped n-material and heavily-doped (conduction-band electrons) metal bounded together.

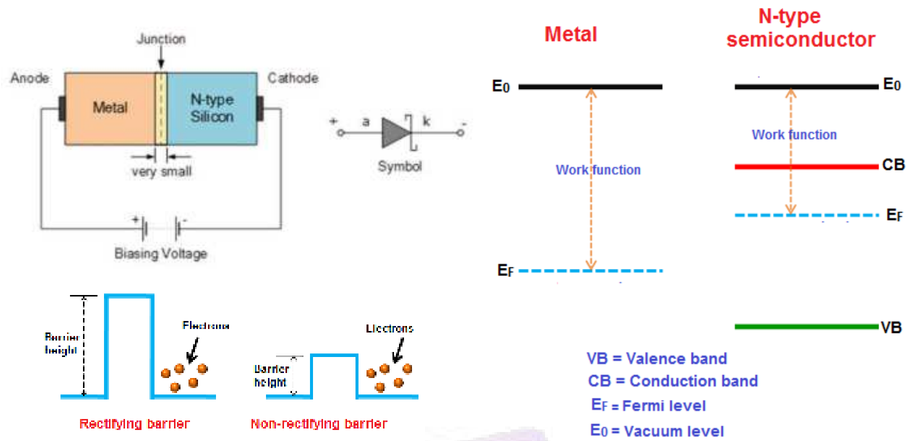
Response is very quick…high speed digital communications.



Lightly doped

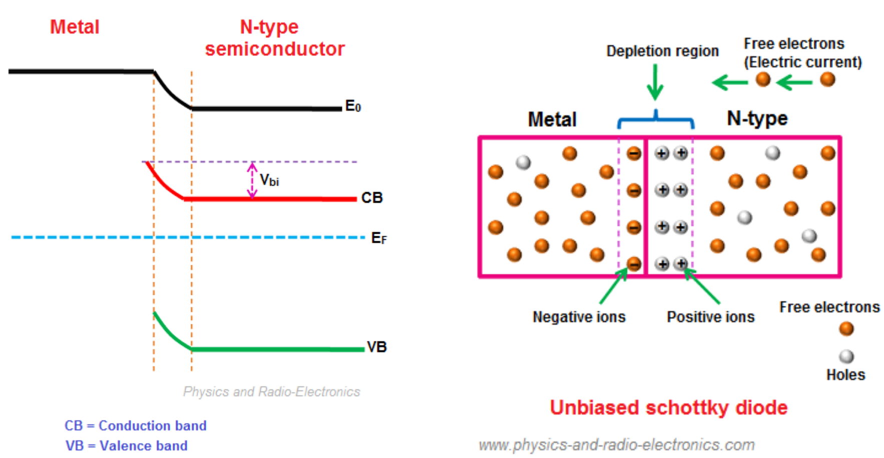
Heavily doped (conduction-band electrons)

Schottky Diode



Non-rectifying metal-semiconductor junction is called ohmic contact. The rectifying metal-semiconductor junction is called non-ohmic contact.

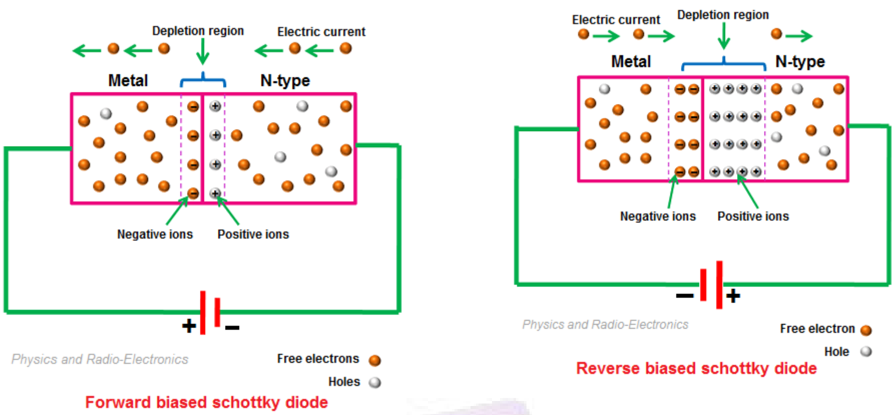
Schottky Diode



CB = Conduction band
VB = Valence band
E_0 = Vacuum level
E_F = Fermi level
V_{bi} = Built-in-voltage barrier

The built-in-voltage (V_{bi}) for schottky diode is given by the difference between the work functions of a metal and n-type S/C.

Schottky Diode



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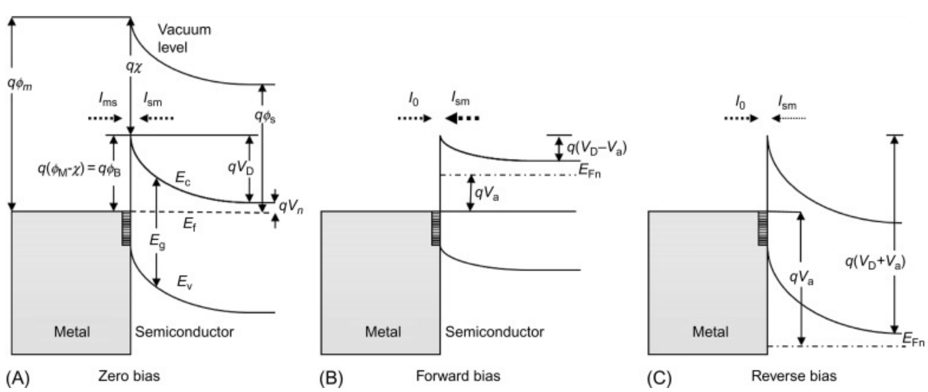
Schottky Diode



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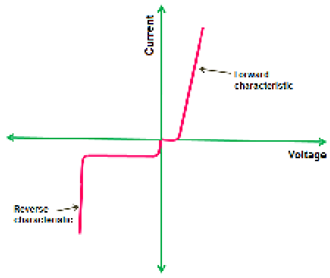
Schottky Diode



V-I characteristics of schottky diode

- Low junction capacitance
- Fast reverse recovery time
- High current density
- Low forward voltage drop or low turn on voltage
- High efficiency
- Operates at high frequencies.
- Schottky diode produces less unwanted noise than pn diode

In schottky diode, the free electrons carry most of the electric current. Holes carry negligible electric current. So schottky diode is a unipolar device. In P-N junction diode, both free electrons and holes carry electric current. So P-N junction diode is a bipolar device.

The reverse breakdown voltage of a schottky diode is very small as compared to the p-n junction diode.

In schottky diode, the depletion region is absent or negligible, whereas in p-n junction diode the depletion region is present.

The turn-on voltage for a schottky diode is very low as compared to the p-n junction diode.

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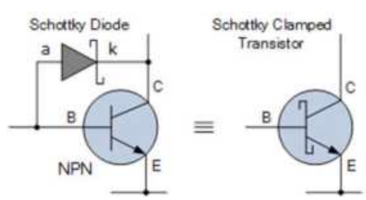
Schottky Diode

All the previous Schottky TTL gates and circuits use a Schottky clamped transistor to prevent them from being driven hard into saturation. As shown, a Schottky clamped transistor is basically a standard bipolar junction transistor with a Schottky diode connected in parallel across its base-collector junction.



When the transistor conducts normally in the active region of its characteristics curves, the base–collector junction is reverse biased and so the diode is reverse biased allowing the transistor to operate as a normal npn transistor. However, when the transistor starts to saturate, the Schottky diode becomes forward biased and clamps the collector-base junction to its 0.4 volt knee value, keeping the transistor out of hard saturation as any excess base current is shunted through the diode.

Preventing the logic circuits switching transistors from saturating decreases greatly their propagation delay time making Schottky TTL circuits ideal for use in flip-flops, oscillators and memory chips.

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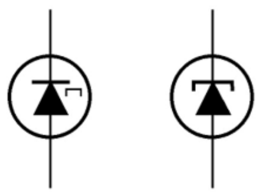
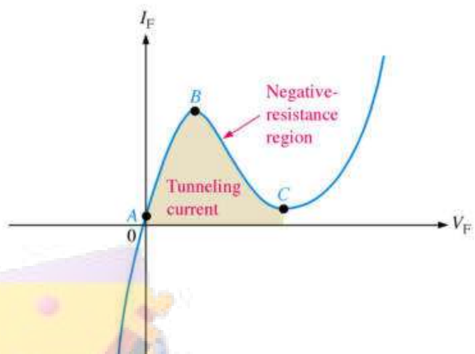
Tunnel Diode

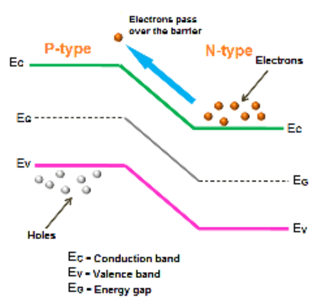
The tunnel diode exhibits negative resistance. It will actually conduct well with low forward bias. With further increases in bias it reaches the negative resistance range where current actually goes down. This is achieved by heavily-doped p and n materials that create a very thin depletion region which permits electrons to "tunnel" through the barrier region.



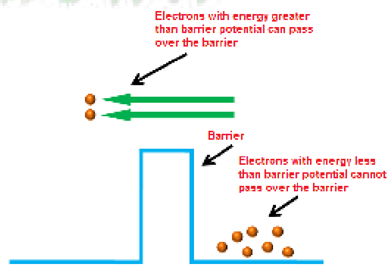
Germanium or Gallium



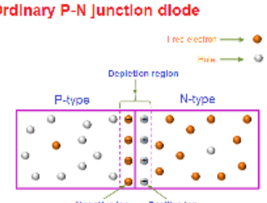
Normal Diode vs. Tunnel Diode



Ordinary P-N junction diode

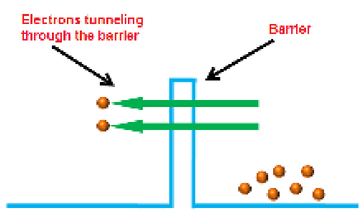


Ordinary p-n junction diode



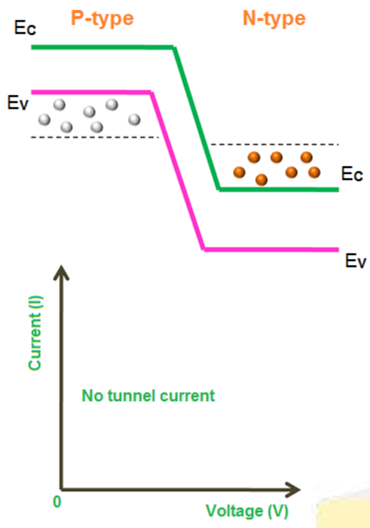
Tunnel diode

Physics and Radio Electronics

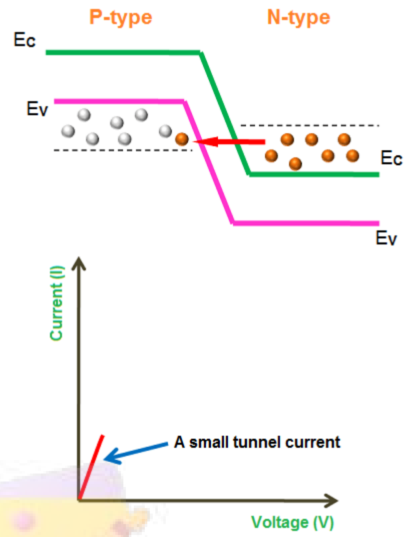


Tunnel diode

Tunnel Diode Working

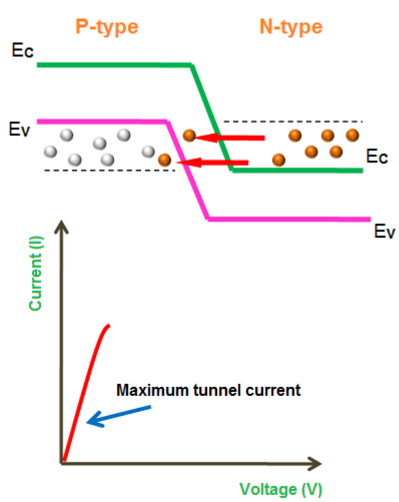


Unbiased tunnel diode

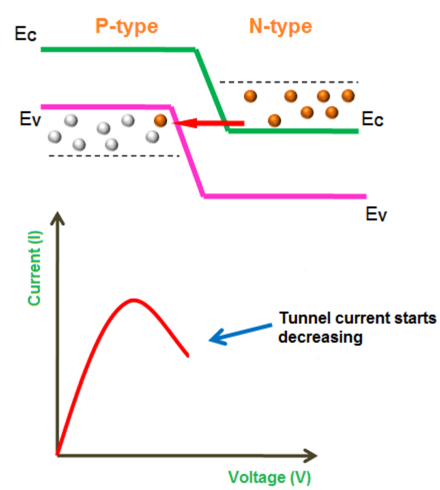


Small tunnel current

Tunnel Diode Working

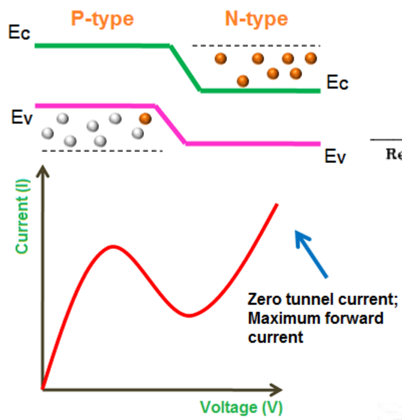


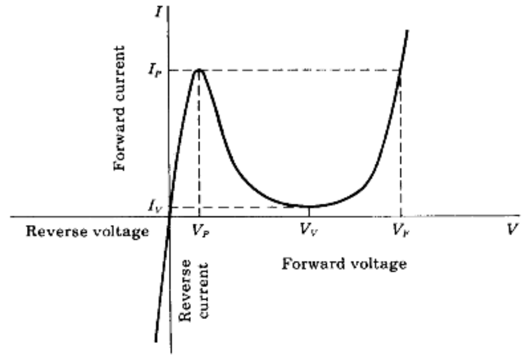
Maximum tunnel current



Tunnel current starts decreasing

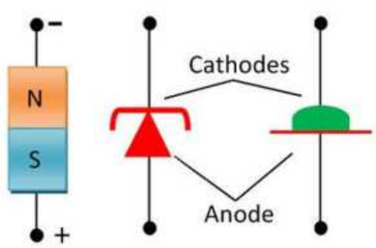
Tunnel Diode Working



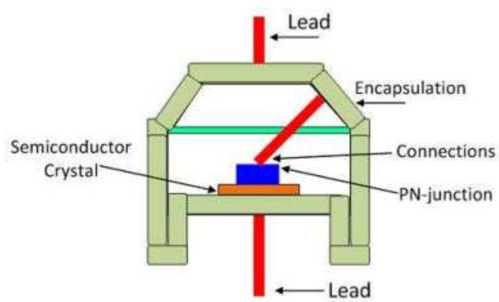


Zero tunnel current; maximum forward current

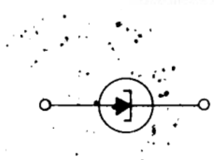
Tunnel Diode



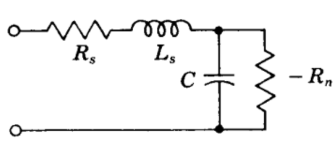
Tunnel Diode Symbols



Pellet Tunnel Diode



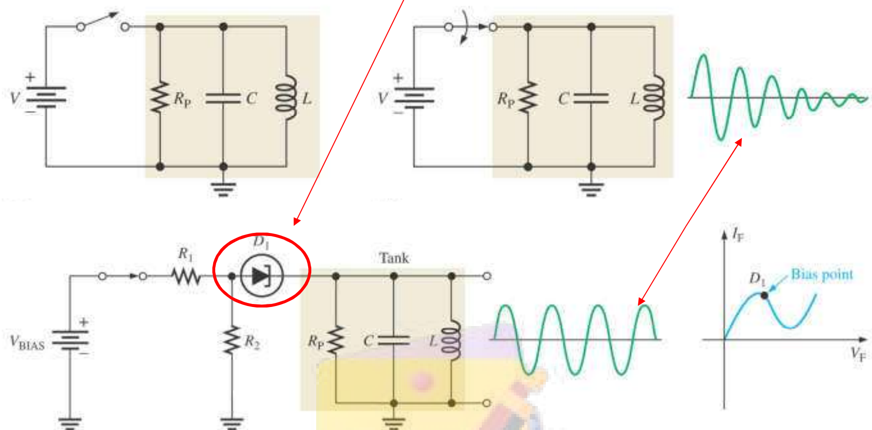
(a)



(b)

Tunnel Diodes

Tank circuits oscillate but "die out" due to the internal resistance. A tunnel diode will provide "negative resistance" that overcomes the losses and maintains the oscillations.



Shockley Diode

The Shockley diode or PNPN diode is a four layer (P-N-P-N), two terminals (namely anode and cathode) semiconductor switching device. It is also called as four layer diode. It functions like a normal diode without any trigger inputs, in reverse biased condition, no current flows through it and in forward biased condition current flows through it when the voltage across it is more than the break over voltage of it.

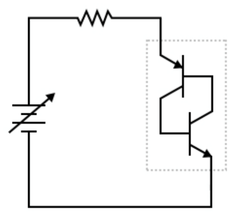
Shockley Diode

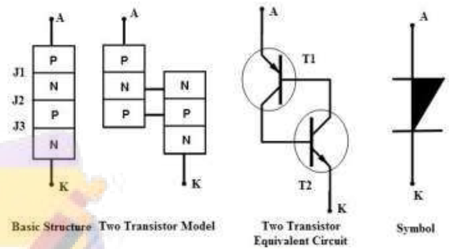
When the voltage is applied to the this diode in such a way that anode is made positive with respect to cathode, junctions J1 and J3 are forward biased and J2 is reverse biased.

Until the voltage across the diode is less than the break over voltage, as an open switch this diode exhibits a very high resistance and allows no current to flow through it.

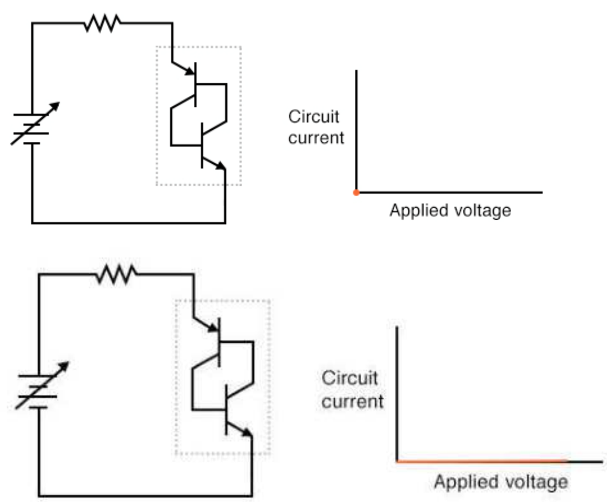
Once the break over voltage is reached (as the forward voltage is increased), it exhibits a very low resistance due to the breakdown of junction J2.

Therefore, it acts like a short circuit and allows the current to flow until the current reaches to the holding current level of the diode. This forward current flow through the diode depends on the voltage applied and the external load resistance.



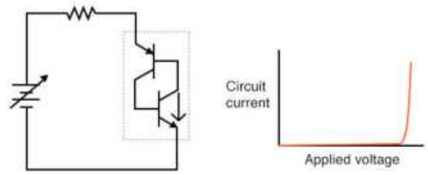


Shockley Diode

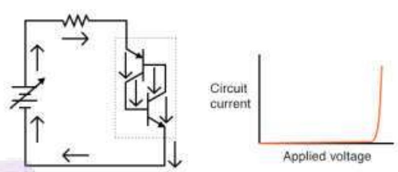


Shockley Diode

As the upper transistor receives base current, it turns on as expected. This action allows the lower transistor to conduct normally, the two transistors "sealing" themselves in the "on" state. Full current is quickly seen in the circuit.

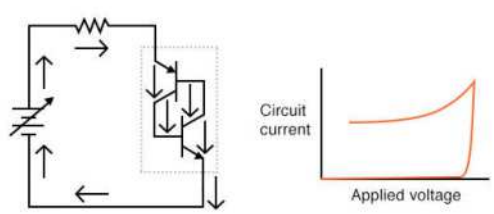


When one transistor breaks down, it allows current through the device structure. This current may be viewed as the "output" signal of the device. Once an output current is established, it works to hold both transistors in saturation, thus ensuring the continuation of a substantial output current. In other words, an output current "feeds back" positively to the input (transistor base current) to keep both transistors in the "on" state, thus reinforcing (or regenerating) itself.

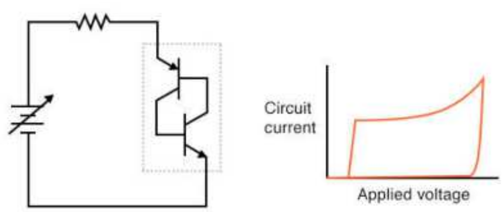


Shockley Diode

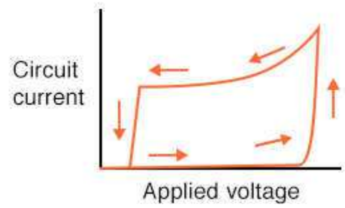
With both transistors maintained in a state of saturation with the presence of ample base current, each will continue to conduct even if the applied voltage is greatly reduced from the breakdown level. The effect of positive feedback is to keep both transistors in a state of saturation despite the loss of input stimulus (the original, high voltage needed to break down one transistor and cause a base current through the other transistor).

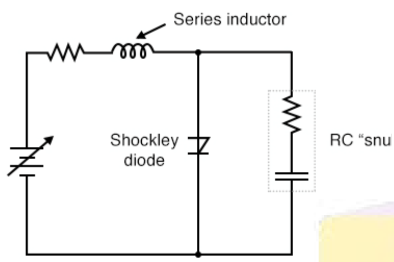


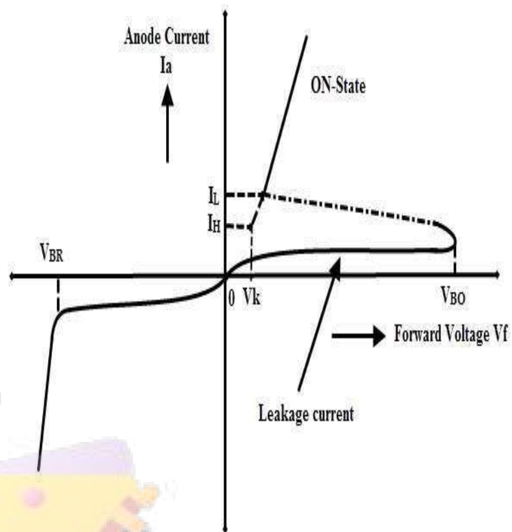
If the DC voltage source is turned down too far, though, the circuit will eventually reach a point where there isn't enough current to sustain both transistors in saturation. As one transistor passes less and less collector current, it reduces the base current for the other transistor, thus reducing base current for the first transistor. The vicious cycle continues rapidly until both transistors fall into cutoff.



Shockley Diode



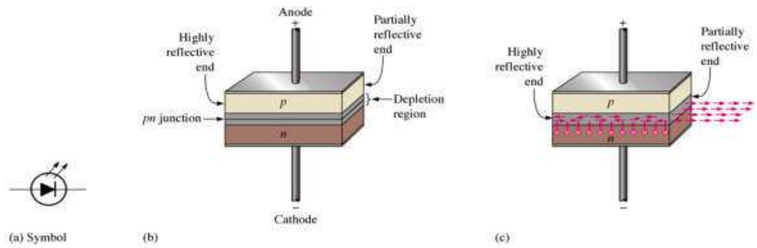




Shockley Diode

Other Diode Types

The laser diode (**l**ight **a**mplification by **s**timulated **e**mission of **r**adiation) produces a monochromatic (single color) "coherent" light. Laser diodes in conjunction with photodiodes are used to retrieve data from compact discs.

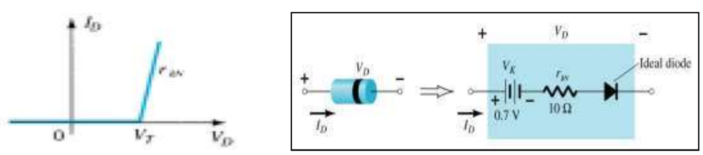


Forward bias the diode and electrons move thru the junction, recombination occurs (as ordinary). Recombinations result in photon release, causing a chain reaction of releases and avalanching photons which form an intense laser beam.

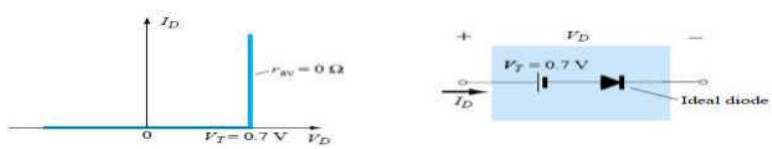
Diode Circuit Analysis

Diode Equivalent Circuit

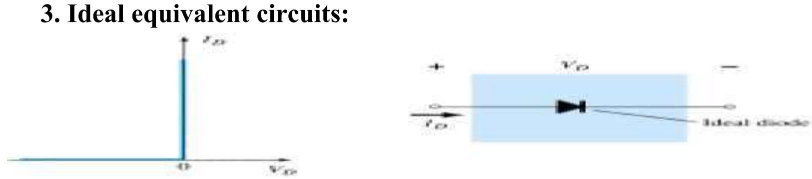
1. Piecewise linear equivalent circuits:



2. Simplified equivalent circuits:

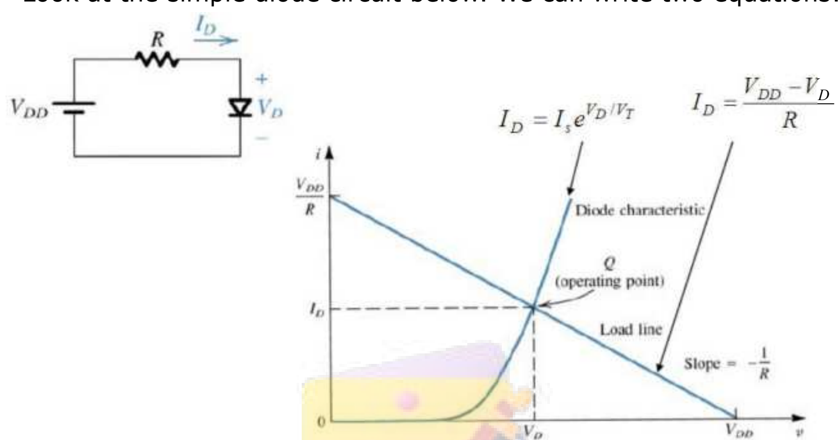


3. Ideal equivalent circuits:



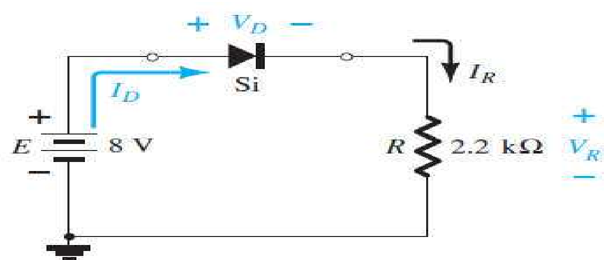
Diode Circuits

- Look at the simple diode circuit below. We can write two equations:



Examples from Text Book

Example: 4 For the series diode configuration shown in fig. determine V_D, V_R and I_D.



Solution:

Since the applied voltage establishes a current in the clockwise direction to match the arrow of the symbol and the diode is in the "on" state,

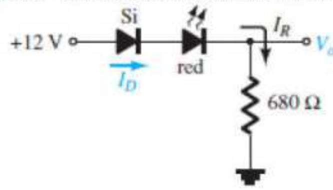
$$V_D = \mathbf{0.7\ V}$$

$$V_R = E - V_D = 8\ V - 0.7\ V = \mathbf{7.3\ V}$$

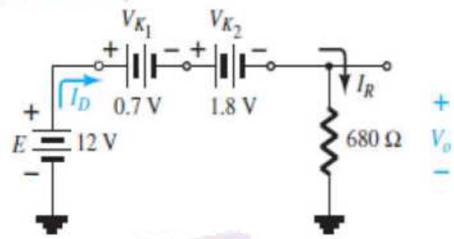
$$I_D = I_R = \frac{V_R}{R} = \frac{7.3\ V}{2.2\ k\Omega} \cong \mathbf{3.32\ mA}$$

Examples

Example: 5 Determine V_o and I_D for the series circuit shown in fig.



Solution: First drawing equivalent ckt;

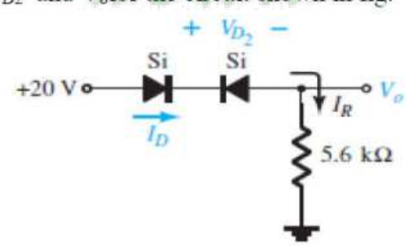


$$V_o = E - V_{K_1} - V_{K_2} = 12\text{ V} - 2.5\text{ V} = \mathbf{9.5\ V}$$

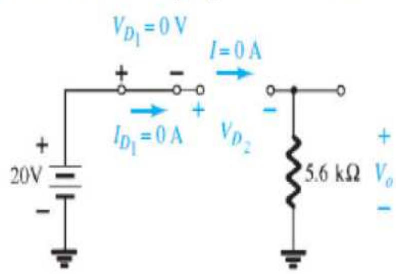
and $$I_D = I_R = \frac{V_R}{R} = \frac{V_o}{R} = \frac{9.5\text{ V}}{680\ \Omega} = \mathbf{13.97\ mA}$$

Examples

Example: 6 Determine I_D, V_{D2} and V_o for the circuit shown in fig.



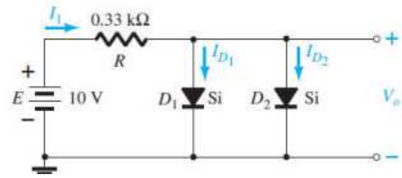
Solution: First drawing equivalent ckt and then analysing ckt;



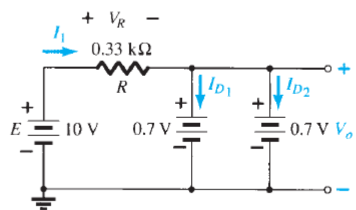
$$V_o = I_R R = I_D R = (0\text{ A})R = \mathbf{0\ V}$$
$$V_{D_2} = V_{\text{open circuit}} = E = \mathbf{20\ V}$$

Examples

Example: 7 Determine V_o, I_1, I_{D1} and I_{D2} for the parallel diode configuration shown in fig.



Solution :



The current

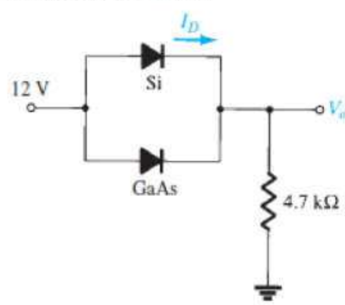
$$I_1 = \frac{V_R}{R} = \frac{E - V_D}{R} = \frac{10\text{ V} - 0.7\text{ V}}{0.33\text{ k}\Omega} = \mathbf{28.18\text{ mA}}$$

Assuming diodes of similar characteristics, we have

$$I_{D_1} = I_{D_2} = \frac{I_1}{2} = \frac{28.18\text{ mA}}{2} = \mathbf{14.09\text{ mA}}$$

Examples

Example: 8 Determine the current I_D for the network.



Solution: Si diode is conducting and GaAs diode is non-conducting because barrier or knee voltage os Si is less than GaAs.

Therfore Current;

$$I_D = \frac{12 - 0.7}{4.7 \times 10^3} = 2.40425\, mA$$