A Handbook on

Electronics Engineering

Revised & Updated

Contains well illustrated formulae & key theory concepts

~~~~~ *For* ~~~~~

ESE, GATE, PSUs
& OTHER COMPETITIVE EXAMS

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A Handbook on Electronics Engineering

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Director's Message

B. Singh (Ex. IES)

During the current age of international competition in Science and Technology, the Indian participation through skilled technical professionals have been challenging to the world. Constant efforts and desire to achieve top positions are still required.

I feel every candidate has ability to succeed but competitive environment and quality guidance is required to achieve high level goals. At MADE EASY, we help you to discover your hidden talent and success quotient to achieve your ultimate goals. In my opinion CSE, ESE, GATE & PSUs exams are tool to enter in to main stream of Nation serving. The real application of knowledge and talent starts, after you enter in to the working system. Here in MADE EASY you are also trained to become winner in your life and achieve job satisfaction.

MADE EASY alumni have shared their winning stories of success and expressed their gratitude towards quality guidance of MADE EASY. Our students have not only secured All India First Ranks in ESE, GATE and PSUs entrance examinations but also secured top positions in their career profiles. Now, I invite you to become alumni of MADE EASY to explore and achieve ultimate goal of your life. I promise to provide you quality guidance with competitive environment which is far advanced and ahead than the reach of other institutions. You will get the guidance, support and inspiration that you need to reach the peak of your career.

I have true desire to serve Society and Nation by way of making easy path of the education for the people of India.

After a long experience of teaching in Electronics Engineering over the period of time MADE EASY team realised that there is a need of good *Handbook* which can provide the crux of Electronics Engineering in a concise form to the student to brush up the formulae and important concepts required for ESE, GATE, PSUs and other competitive examinations. This *handbook* contains all the formulae and important theoretical aspects of Electronics Engineering. It provides much needed revision aid and study guidance before examinations.

B. Singh (Ex. IES)
CMD, MADE EASY Group

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C O N T E N T S

A Handbook on Electronics Engineering

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Electronic Devices and Circuits

Energy Bandgap

- Difference between the lower energy level of conduction band E_c and upper energy level of valence band E_v is called **energy band gap**.

$$E_g = E_c - E_v$$

- In **metals** the conduction band is either partially filled or overlaps the valence band.
- In **insulator** energy band gap is very high.
- In **semiconductor** band gap is relatively small.
- An empty state in valence band is referred as hole.
- A perfect semiconductor crystal with no impurities or lattice defects is called **intrinsic** semiconductor.
- When a semiconductor is doped such that equilibrium concentration n_0 and p_0 are different from intrinsic carrier concentration n_i, the material is said to be **extrinsic**.

Fermi Level

- Fermi level is energy state having probability '1/2' of being occupied by an electron if there is no forbidden band.
- Energy of fastest moving electron at 0 K is called Fermi energy.
- **Fermi Dirac distribution function** $f(E)$ gives the probability that an available energy state E will be occupied by an electron at absolute temperature T, under conditions of thermal equilibrium

$$f(E) = \frac{1}{1+ \exp[(E - E_F)/kT]}$$

where, $E_F \rightarrow$ Fermi energy level ; $K \rightarrow$ Boltzmann's constant
$T \rightarrow$ Absolute temperature in Kelvin

- The Fermi Dirac distribution function is given as

Note: ....

☑ [1 − $f(E)$] gives the probability that energy state E will be occupied by a hole.

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Density of States

The density of allowed energy states per energy range per unit volume. Density of states in conduction band

$$\rho_c(E) = 4\pi \left(\frac{2m_n^*}{h^2} \right)^{3/2} (E - E_c)^{1/2}$$

where, $m_n^* \rightarrow$ Effective mass of electrons ; $E_c \rightarrow$ Energy level of lowest conduction level ; $h \rightarrow$ Plank's constant

Density of states in valence band , $\rho_v(E) = 4\pi \left(\frac{2m_p^*}{h^2} \right)^{3/2} (E_v - E)^{1/2}$

where, $m_p^* \rightarrow$ Effective mass of holes ; $E_v \rightarrow$ Highest energy level of valence band

Concentration of Carriers

- Concentration of electrons in conduction band, $n_0 = \int\limits_{E_c}^{\infty} \rho_c(E) \, f(E) \, dE$

- Concentration of electrons in conduction band is given by
$$n_0 = N_c \, e^{-(E_C - E_F)/kT}$$
where, $n_0 \rightarrow$ Concentration of e^-_s in conduction band; $E_F \rightarrow$ Fermi energy level ; $k \rightarrow$ Boltzmann's constant ; $T \rightarrow$ Absolute temperature ; $N_C \rightarrow$ Effective density of states in conduction band

- Effective density of states N_C is given by, $N_C = 2\left[\frac{2\pi m_n^* kT}{h^2} \right]^{3/2}$

- Concentration of holes in valence band , $p_0 = \int\limits_{-\infty}^{E_v} \rho_v(E) \left[1 - f(E) \right] dE$

- Concentration of holes in valence band is given by
$$p_0 = N_v \, e^{-(E_F - E_v)/kT}$$
where, $p_0 \rightarrow$ Concentration of holes ; $N_v \rightarrow$ Effective density of states in valence band ; $E_F \rightarrow$ Fermi energy level

- Effective density of sates in valence band is given by

$$N_v = 2\left[\frac{2\pi m_p^* kT}{h^2}\right]^{3/2}$$

Mass Action Law

- It states that at thermal equilibrium product of concentration of free electrons and holes is equal to the square of intrinsic concentration at that temperature i.e.

$$n_0 p_0 = n_i^2$$

where, $n_0 \rightarrow$ Concentration of electron in conduction band ;

$p_0 \rightarrow$ Concentration of holes in valence band ; $n_i \rightarrow$ Intrinsic concentration at given temperature

- Intrinsic concentration is given by

$$n_i = \sqrt{N_c N_v}\, e^{-E_g/2kT} \; ; \text{ where, } E_g \rightarrow \text{band gap}$$

- n_i can also be given as

$$n_i^2 = A_0\, T^3\, e^{-E_g/kT} \; ; \text{ where, } A_0 \rightarrow \text{is a constant}$$

- Concentration of electrons in conduction band can also be given as

$$n_0 = n_i\, e^{(E_F - E_i)/kT}$$

where, $E_i \rightarrow$ intrinsic level lies near the middle of bandgap

- Concentration of holes in valence band can also be given as

$$p_0 = n_i\, e^{(E_i - E_F)/kT}$$

Note: ....

☑ Intrinsic concentration depends on temperature. As temperature increases the intrinsic concentration increases as $T^{3/2}$.

☑ Mass action law is applicable to non-degenerate or lightly doped materials. For degenerate materials, it is modified as

$$np = n_i^2\, e^{\frac{\Delta E_g}{kT}}$$

The ΔE_g term appears because of splitting of the energy levels due to heavy doping which leads the reduction in energy band gap by ΔE_g.

Space Charge Neutrality

- If the material is to remain electrostatically neutral, the sum of positive charges must balance the sum of negative charges i.e.

$$p_0 + N_d^+ = n_0 + N_a^-$$

where, $N_d^+ \rightarrow$ concentration of donor atoms ; $N_a^- \rightarrow$ concentration of acceptor atoms ; $p_0 \rightarrow$ concentration of holes ; $n_0 \rightarrow$ concentration of electrons

Doping in Semiconductors

For N-type semiconductors

$$n \cong N_d^+$$

$$p = \frac{n_i^2}{N_d^+}$$

For p-type semiconductors

$$p \cong N_a^-$$

$$n = \frac{n_i^2}{N_a^-}$$

Note: ....

☑ Expression for p and n is above equations are approximate under the assumption that $N_d^+ \gg n_i$, $N_a^- \gg n_i$.

☑ Exact expressions are:

$$n = \frac{N_d^+ + \sqrt{(N_d^+)^2 + 4n_i^2}}{2} \quad p = \frac{N_a^- + \sqrt{(N_a^-)^2 + 4n_i^2}}{2}$$

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Mobility of Charge Carriers

• It is drift velocity per unit electric field. $\left(\text{Unit} \rightarrow \dfrac{m^2}{V\text{-}s} \right)$

• It defines how fast the charge carrier travels from one place to other and is given by

$$\mu = \frac{v_d}{E}$$

where, $v_d \rightarrow$ Drift velocity ; $E \rightarrow$ Electric field

	Ge	Si
e⁻ mobility	3800 cm²/V sec	1300 cm²/V sec
hole mobility	1800 cm²/V sec	500 cm²/V sec

• e⁻ mobility — Ge: $3800 \text{ cm}^2/\text{V sec}$ — Si: $1300 \text{ cm}^2/\text{V sec}$
hole mobility — Ge: $1800 \text{ cm}^2/\text{V sec}$ — Si: $500 \text{ cm}^2/\text{V sec}$

Note: ....

☑ Electron's mobility is always greater than hole mobility in a given material. Hence electron can travel faster so contribute more current for same electric field than hole as explained by quantum mechanical physics.

....

• Mobility of charge carriers decreases with temperature and varies as

$\mu \propto T^{-m}$; where, m is a constant

In Ge, $m = 1.66$ for e⁻ and 2.33 for hole
In Si, $m = 2.5$ for e⁻ and 2.7 for hole

• Mobility also varies with applied electric field as

Note: ....

☑ At smaller electric field mobility is constant.

☑ At very high electric field product of mobility and electric field becomes constant and is equal to saturation value of drift velocity.

Effect of Scattering on Mobility

• The two types of scattering mechanism are: Lattice Scattering and Impurity Scattering.

• The variation of mobility in accordance with scattering is shown as

• Overall mobility is given by

$$\frac{1}{\mu} = \frac{1}{\mu_1} + \frac{1}{\mu_2} + \frac{1}{\mu_3} + \ldots\ldots$$

where, $\mu \rightarrow$ overall mobility ; μ_1, μ_2, $\mu_3 \rightarrow$ Mobility corresponding to different scattering mechanism

Energy Gap (E_g) Variations

• Energy gap depends on temperature and interatomic spacing.

• Variation of energy gap with temperature is as

$$E_g = E_{g0} - \beta_0 T \text{ eV}$$

where, $E_{g0} \rightarrow$ Energy gap at 0 K, $\beta_0 \rightarrow$ material constant,

$\beta_0 = 2.2 \times 10^{-4}$ eV/K for Ge = 3.6×10^{-4} eV/K for Si

$E_g \rightarrow$ energy gap at temperature T(K)

Note: ....

☑ E_{g0} – 0.785 eV(Ge), 1.21 eV(Si)
☑ E_{g300} – 0.72 eV (Ge), 1.1 eV(Si)
☑ E_{g300} – 1.47 eV (GaAs)
....

Hall Effect

• Hall voltage is measured w.r.t. upper surface of specimen figure.
• It states that if a specimen (metal or semiconductor) carrying a current I is placed in transverse magnetic field B, an electric field is induced in a direction perpendicular to both I and B.

• Hall Voltage (V_H) is given by , $V_H = Ed$ or $V_H = \dfrac{BI}{\rho W}$

   where, $E \rightarrow$ Electric field induced ; $d \rightarrow$ Separation between upper and lower surface of specimen or height of specimen ; $W \rightarrow$ Width of specimen ; $B \rightarrow$ Applied magnetic field ; $I \rightarrow$ Current flowing in specimen ; $\rho \rightarrow$ Charge density

• $\dfrac{1}{\rho}$ is called **Hall coefficient** R_H i.e. $R_H = \dfrac{1}{\rho}$

• V_H can also be given as $V_H = R_H \dfrac{BI}{W}$

• By hall experiment, mobility is given by $\mu = \dfrac{8}{3\pi}\sigma R_H$

   where, $\mu \rightarrow$ Mobility of charge carriers ; $\sigma \rightarrow$ Conductivity of material

Note: ....

☑ Hall effect is utilized in determining whether a given material is metal, n-type SC or p-type SC.
☑ For metal, value of V_H is lesser compared to SC.
☑ Hall voltage is negative for metal or n-type SC.
☑ Hall voltage is positive for p-type SC.
☑ Hall voltage is zero for intrinsic SC.

☑ It can be used in finding mobility of charge carries, concentration of charge carriers, and type of semiconductor.

☑ It is utilized in Hall effect multiplier.

☑ In metal, R_H increases with temperature.

☑ In pure SC, R_H decreases with temperature.

☑ In extrinsic SC, R_H is independent of temperature.

Conductivity (σ)

$$\sigma = q \cdot n\mu_n + qp\mu_p$$

where, $n \to$ Concentration e^-_s in conduction band ; $p \to$ Concentration of holes in valence band ; $\mu_n \to$ Mobility of e^-_s ; $\mu_p \to$ Mobility of holes

• Conductivity of pure SC is given by, $\sigma = qn_i[\mu_n + \mu_p]$

where, $n_i \to$ Intrinsic concentration

Note:

☑ Conductivity of pure SC increases with temperature.

☑ Conductivity of pure SC at 0 K is zero.

• Conductivity of extrinsic SC is given by

$\sigma \cong qN_d\,\mu_n$ for n-type ; where, $N_d \to$ donor concentration

$\sigma \cong qN_a\mu_p$ for p-type ; $N_a \to$ acceptor concentration

Note:

☑ Conductivity of extrinsic SC at 0 K is zero.

☑ Conductivity of extrinsic SC initially increases when temperature rises above 0 K.

☑ Conductivity of extrinsic SC decreases with increase in temperature above normal temperature.

☑ At Curie temperature, conductivity becomes equal to intrinsic conductivity.

☑ Conductivity increases with increase in doping concentration.

Fermi Level in Intrinsic and Extrinsic SC

• Fermi level E_F in *intrinsic* SC is given by

$$E_F = \frac{E_C + E_V}{2} - \frac{kT}{2}ln\left(\frac{N_C}{N_V}\right)$$

Note: ....

- ☑ If $N_V \cong N_c$ then fermi level lies in the middle of energy gap.
- ☑ At 0 K Fermi level lies in the middle of energy gap.
- ☑ Fermi level in pure SC depends on temperature.
- ☑ As temperature increases, fermi level moves away from the middle of bandgap.

....

- Fermi level in **n-type** SC is given by, $E_F = E_C - kT \ln\left(\dfrac{N_C}{N_D}\right)$

  where, $N_C \rightarrow$ density of states in conduction band ; $N_D \rightarrow$ donor concentration

Note: ....

- ☑ In n-type SC fermi level depends on both temperature and donor concentration.
- ☑ At 0 K Fermi level coincides with E_C.
- ☑ As temperature increases fermi level moves towards the middle of bandgap.
- ☑ For $N_C = N_D$, E_F coincides with E_C.
- ☑ Normally fermi level lies close to E_C.
- ☑ At room temperature, E_F exists just below the donor energy level.

....

- Fermi level in **p-type** SC is given by, $E_F = E_v + kT \ln \dfrac{N_V}{N_A}$

  where, $N_V \rightarrow$ density of states in valence band ; $N_A \rightarrow$ concentration of acceptors

Note: ....

- ☑ In p-type SC fermi level E_F at 0 K coincides with E_V.
- ☑ In p-type SC fermi level lies close to valence band.
- ☑ In p-type SC fermi level moves away from valence band as temperature increases.
- ☑ In p-type SC fermi level moves towards valence band as N_A increases and attains a saturation value of E_v at $N_A = N_V$. At room temperature, E_F exists just above the accepter energy level.

....

- Shift in the position of fermi level with respect to intrinsic fermi level in n-type SC due to doping is given by

$$\text{Shift} = kT \, In\left(\frac{n}{n_i}\right) \simeq kT \, In\left(\frac{N_D}{n_i}\right) \text{ upwards}$$

- Shift in position of fermi level in p-type SC with respect intrinsic fermi level due to doping is given by

$$\text{Shift} = kT \, In\frac{p}{n_i} \cong kT \ln\frac{N_A}{n_i} \text{ downwards}$$

Remember: ....

☑ In a material at equilibrium there is no discontinuity in fermi level. More generally we can say that fermi level at equilibrium must be constant throughout the material i.e.

$$\frac{dE_F}{dx} = 0$$

☑ In a semiconductor minimum conductivity occurs at:

$$n = n_i\sqrt{\frac{\mu_p}{\mu_n}} \;\; ; \;\; p = n_i\sqrt{\frac{\mu_n}{\mu_p}} \;\; ; \;\; \sigma_{min} = 2n_iq\sqrt{\mu_n\,\mu_p}$$

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II   Excess Carriers in Semiconductor

Introduction

- Let us assume that excess electron and hole concentration is created in a p-type SC at $t = 0$ and initial concentration of excess electrons and holes is Δn and Δp, then concentration of excess electrons at any other time t is given by

$$\delta(t) = \Delta n e^{-t/\tau_n}$$

where, $\tau_n \rightarrow$ Recombination life time or minority carrier life time.
                $\Delta n \rightarrow$ Concentration at t = 0

$$\tau_n = (\alpha_r \, p_0)^{-1}$$

where, $\alpha_r \rightarrow$ Constant of proportionality for recombination
                $p_0 \rightarrow$ Concentration of holes

- A more general expression for carrier life time is given by

$$\tau_n = \frac{1}{\alpha_r(n_0 + p_0)} \; ; \text{ valid for low level injection only}$$

Steady State Carrier Generation (Quasi Fermi Level)

- If we optically generate excess charge carriers in a SC by shining light on it then optical generation rate is given by

$$g_{op} = \frac{\delta n}{\tau_n}$$

where, $\delta n \rightarrow$ equilibrium excess concentration electrons

$$\tau_n = \frac{1}{\alpha_r (n_0 + p_0)}$$

$$\delta n = \delta p$$

$\delta p \rightarrow$ excess hole concentration ; $g_{op} \rightarrow$ optical generation rate

- When excess carrier are generated then there exist different fermi levels F_n and F_p for electron and hole called quasi fermi level.
- Carrier concentration (resulting) is given by

$$n = n_i\, e^{(F_n - E_i)/kT} \quad ; \quad p = n_i\, e^{(E_i - F_p)/kT}$$

where, $E_i \rightarrow$ intrinsic fermi level ; $F_n \rightarrow$ fermi level for $e^-{}_s$;
$F_k \rightarrow$ fermi level for holes ; $n \rightarrow$ net concentration of $e^-{}_s$
$p \rightarrow$ net concentration of holes

Diffusion Process

- Diffusion is the natural result of the random motion of the individual molecules.
- Diffusion happens due to concentration gradient.
- Diffusion current density is given by

$$J_n(diff) = q D_n \frac{d\,n(x)}{dx} \quad ; \quad J_p(\text{diff}) = -q D_p \frac{d\,p(x)}{dx}$$

where, J_n(diff) $\rightarrow$ diffusion current density due to electrons ;
J_p(diff) $\rightarrow$ diffusion current density due to holes ; $D_n \rightarrow$ electron diffusion coefficient; $D_p \rightarrow$ hole diffusion coefficient; $n(x) \rightarrow$ profile of $e^-{}_s$ with respect to x ; $p(x) \rightarrow$ profile of holes with respect to x

Drift Process

- Transport of carriers under the influence of applied electric field.
- J_n(drift) $= n\, q\, \mu_n\, E \quad ; \quad J_p$(drift) $= n\, q\, \mu_p\, E$
  where, J_n(drift) $\rightarrow$ Drift current density due to electrons ; J_p(drift) $\rightarrow$ Drift current density due to holes ; $n, p \rightarrow$ Concentration of electron and holes respectively ; $E \rightarrow$ Applied Electric Field

Total Current Density

- Overall current density is given by, $J_n(x) = q\mu_n E(x)n(x) + qD_n\dfrac{dn(x)}{dx}$

$$J_p(x) = q\mu_p\, p(x)E(x) - qD_p\dfrac{dp(x)}{dx} \;;\; J(x) = J_n(x) + J_p(x)$$

where, $J(x) \to$ Overall current density; $J_n(x) \to$ Current density due to e$_s^-$;
$J_p(x) \to$ Current density due to holes ; $E(x) \to$ Electric field applied

Einstein Relation

- This gives the relation between diffusion coefficient (D), mobility (μ) and temperature and given as

$$\dfrac{D_n}{\mu_n} = \dfrac{D_p}{\mu_p} = \dfrac{kT}{q} \;;\; \text{where, } \dfrac{kT}{q} = V_T \to \text{Thermal voltage}$$

Continuity Equation

- This equation is given by

$$\dfrac{\partial\delta p}{\partial t} = -\dfrac{1}{q}\dfrac{\partial J_p}{\partial x} - \dfrac{\delta p}{\tau_p} \;\;;\; \dfrac{\partial\delta n}{\partial t} = \dfrac{1}{q}\dfrac{\partial J_n}{\partial x} - \dfrac{\delta n}{\tau_n}$$

where, $\delta p, \delta n \to$ Excess carrier concentration
$\tau_n, \tau_p \to$ Carrier life time for e$_s^-$ and holes respectively

- Another form of this equation is given by

$$\dfrac{\partial\delta n}{\partial t} = D_n\dfrac{\partial^2\delta n}{\partial x^2} - \dfrac{\delta n}{\tau_n} \;\;\;;\; \dfrac{\partial\delta p}{\partial t} = D_p\dfrac{\partial^2\delta p}{\partial x^2} - \dfrac{\delta p}{\tau_p}$$

Diffusion Length

- Diffusion length for electrons is given by , $L_n = \sqrt{D_n\tau_n}$
  where, $L_n \to$ Diffusion length for electron ; $D_n \to$ Diffusion coefficient for electron ; $\tau_n \to$ Carrier life time for electron

- Diffusion length for holes is given by, $L_p = \sqrt{D_p\tau_p}$
  where, $L_p \to$ Diffusion length for holes ; $D_p \to$ Holes diffusion coefficient ; $\tau_p \to$ Carrier life time for holes

- If excess carrier concentration Δn and Δp are introduced at $x = 0$ in n-type material then at any other x excess carrier concentration will be

$$\delta p(x) = \Delta p e^{-x/L_p}$$

where, $\Delta p \to$ Excess holes concentration at $x = 0$; $\delta p(x) \to$ Excess holes concentration at any x ; $L_p \to$ Diffusion length for hole

Direct Bandgap SC

- Most of falling e^-_s will be directly releasing the energy in the form of light and hence called ***direct bandgap*** SC.
- During e^-_s falling from conduction band to valence band the energy of e^- changes (both K.E. and P.E.).
- Momentum of e^-_s will remain same.
- Carrier life time is comparatively less. Ex. $\rightarrow$ GaAs.

Indirect Bandgap SC

- Most of falling e^-_s will be directly releasing the energy in form of heat.
- Momentum of e^-_s will change.
- Larger carrier life time. Ex. $\rightarrow$ Si, Ge.

Note: ....

☑ Direct bandgap materials having higher carrier life time are used for fabrication of Laser.

☑ When minority carriers are injected into extrinsic SC they flow inside SC due to diffusion in absence of electric field.

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III Junction Diode

Basic Structure

$$E = \int \frac{\rho}{\varepsilon} dx$$

$$V = -\int E dx$$

Contact Potential or Built-in Potential (V_0)

$$V_0 = \frac{kT}{q} \ln \left[\frac{N_a N_d}{n_i^2} \right]$$

where, $V_0 \rightarrow$ Contact potential ; $k \rightarrow$ Boltzmann's constant $(1.38 \times 10^{-23}$ J/K) ; $q \rightarrow$ Electron charge $(1.6 \times 10^{-19}$ coulomb) ; $T \rightarrow$ Temperature in Kelvin of p-n junction ; $N_a \rightarrow$ Concentration of acceptors (/cm^3) on p-side ; $N_d \rightarrow$ Concentration of donors (/cm^3) on n-side ; $n_i \rightarrow$ Intrinsic concentration (/cm^3) at given temperature

Maximum Electric Field

Maximum electric field is given by, $E_0 = -\frac{q}{\in} \cdot N_d \, x_{n0} = -\frac{q}{\in} N_a \, x_{p0}$

where, $x_{n0} \rightarrow$ Width of depletion region on *n*-side ; $x_{p0} \rightarrow$ Width of depletion region on *p*-side ; $\in \rightarrow$ Permittivity of material from which diode is made

Note: ....

☑ Contact potential in the terms of maximum electric field is given by

$$V_0 = -\frac{1}{2} E_0 W$$

where, $V_0 \rightarrow$ Contact potential ; $E_0 \rightarrow$ Maximum electric field at junction ; $W \rightarrow$ Width of depletion region

☑ Negative sign is due to the fact that this electric field is from n to p.

☑ In case of unbiased p-n junction diode electric field is maximum at the junction and decreases on the two sides of junction and is zero outside the space charge region.

....

Width of Depletion Region

Width of depletion region in unbiased condition is given by

$$W = \left[\frac{2 \in V_0}{q} \left(\frac{N_a + N_d}{N_a N_d} \right) \right]^{1/2}$$

Note: ....

☑ If we reverse bias the diode by voltage V then in formulae of depletion width V_0 is replaced by $\left| V_0 + V \right|$.

☑ Depletion width increases with reverse and decreases with forward biased.

☑ Depletion approximation is assumed in calculating the above equations.

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Charge Neutrality Equation

$$x_{n0}N_d = x_{p0}N_a \quad \text{also} \quad x_{n0} + x_{p0} = W$$

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☑ For a linearly graded junction with the charge density increasing linearly from p-region to n-region as $\rho = \alpha qx$.

The depletion width is given as
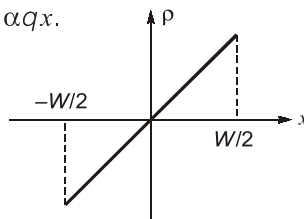
$$W = \left(\frac{12 \in V_o}{\alpha q} \right)^{1/3}$$

where, $\alpha \rightarrow$ Impurity gradient

$q \rightarrow$ Charge of electron

$\in \rightarrow$ Permittivity of material ; $V_o \rightarrow$ Contact potential

☑ Maximum Electric Field for such a junction is given as

$$\left| E_{max} \right| = \frac{\alpha q W^2}{8 \in}$$

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Current Equation

$$I_f = I_0 \left[e^{V_d/\eta V_T} - 1 \right]$$

where, $I_0 \rightarrow$ Reverse saturation or leakage current ; $V_d \rightarrow$ Forward biased voltage ; $\eta \rightarrow$ Recombination factor (material constant) = 1 for Ge = 2 for Si ; $V_T \rightarrow$ thermal voltage ; $V_T = kT/q$ = 0.0259 V at room temperature

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☑ $I_f \rightarrow$ is majority carrier current and diffusion current.

☑ $I_0 \rightarrow$ drift current

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● Reverse saturation current (I_0) doubles for every 10°C rise in temperature.

$$I_{o(T_2)} = I_{o(T_1)} \times 2^{(T_2 - T_1)/10}$$

where, $I_{o(T_2)} \rightarrow$ Reverse saturation current at temperature T_2

$I_{o(T_1)} \rightarrow$ Reverse saturation current at temperature T_1

here, $T_2 > T_1$

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☑ I_0 depends on temperature and is minority carrier current.

☑ I_f (forward diode current) is independent of temperature.

☑ Forward voltage across diode decreases with the temperature.

☑ For 1°C rise in temperature it decreases by 2.5 mV

$$\frac{dV}{dT} = -2.5 \text{ mV/°C}$$

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$$I_o = Aqn_i^2 \left[\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A} \right]$$

where, $A \rightarrow$ Area of cross-section ; D_p, $D_n \rightarrow$ Diffusion constant of holes and electrons respectively ; L_p, $L_n \rightarrow$ Diffusion length of holes and electrons respectively

Diode Resistance

- Dynamic or incremental resistance of diode, $r = \dfrac{\eta V_T}{I_f} = \dfrac{dV}{dI}$

  where, $\eta \rightarrow$ recombination factor = 1 for Ge = 2 for Si
        $I_f \rightarrow$ forward current, $V_T \rightarrow$ thermal voltage

- Static resistance, $R = \dfrac{V}{I}$

Note: ....

☑ Static resistance is always greater than A.C. or dynamic resistance.

....

Junction Capacitance

- Junction capacitance, $C_j = \dfrac{A\in}{W}$

  where, $A \rightarrow$ Area of cross-section of diode ; $W \rightarrow$ Width of depletion region ; $\in \rightarrow$ Permittivity of material

- Depletion layer in a *p-n* junction behave as a parallel plate capacitance and capacitance is given by

$$C_j = \left| \frac{dQ}{d(V_0 - V)} \right| = \frac{A}{2} \left[\frac{2q\in}{(V_0 - V)} \frac{N_a N_d}{N_a + N_d} \right]^{1/2}$$

where, $V \rightarrow$ Applied voltage ; $A \rightarrow$ Area of cross-section

Remember: ....

☑ $C_j \propto \dfrac{1}{(V_0 - V)^{1/2}}$

☑ C_j is voltage variable capacitance.

☑ In case of reverse bias transition capacitance C_T is same as junction capacitance.

☑ In reverse biased diode, transition capacitance varies as

$$C_T \propto V^{-n}$$

where, $V \rightarrow$ applied reserve voltage

$$n = \frac{1}{2} \text{ for step graded diode } (p^+n \text{ or } p\text{–}n^+)$$

$$= \frac{1}{3} \text{ for linear graded diode } (p^+ \, n^+)$$

$$= \frac{1}{2.5} \text{ for diffused } p\text{-}n \text{ junction diode}$$

....

Diffusion Capacitance or Storage Capacitance (C_D)

- C_D is junction capacitance in forward biased diode.
- $C_D > C_T$ always

$$C_D \propto \sqrt{\text{doping}} \ ; \ C_D \propto I_f \ ; \ C_D = \tau \cdot g$$

where, $\tau \rightarrow$ Mean life time of minority carriers on either side or time constant of diode ; $g \rightarrow$ Dynamic conductance of diode

$$g = \frac{I_f}{\eta V_T}$$

so $\qquad\qquad C_D = \dfrac{\tau I_f}{\eta V_T} \ \text{ Farads}$

- Diffusion capacitance of diode when it is operated with sinusoidal signal

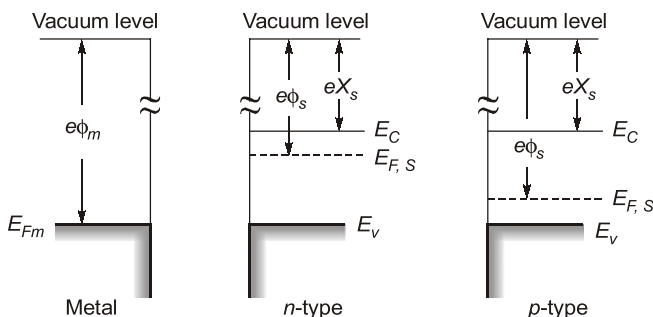 (C_D') is $C_D' = \dfrac{1}{2}\tau \cdot g$ at low frequency

- At high frequency, $C_D' = \left(\dfrac{\tau}{2\omega}\right)^{1/2} \cdot g$

  where, $\omega \rightarrow$ Angular frequency ; $\tau \rightarrow$ Time constant of diode ; $g \rightarrow$ Dynamic conductance of diode
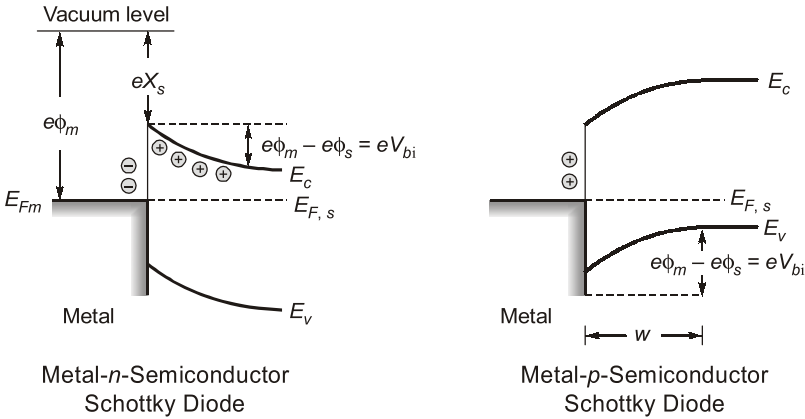
Metal Semiconductor Junctions

- Metal-semiconductor junctions are of two types-ohmic contact and Schottky junction.
- Band profile of disconnected metal and semiconductors can be drawn as:

where, $\phi_m \rightarrow$ Work function of metal ; $X_s \rightarrow$ Electron affinity ; $E_{F,m} \rightarrow$ Fermi level of metal ; $E_{F,s} \rightarrow$ Fermi level of semiconductor ; E_c, $E_v \rightarrow$ Conduction and valence energy levels respectively

- Formation of Schottky junction takes place when metal and semiconductor are brought closer.

Metal-*n*-Semiconductor
Schottky Diode

Metal-*p*-Semiconductor
Schottky Diode

where, $V_{bi} \rightarrow$ Built in potential ; $W \rightarrow$ Width of depletion region

- The difference between *p-n* diodes and Schottky diodes can be tabulated as

p-n Diode	Schottky Diode
1. The forward bias needed to make the device conducting (cut-in voltage) is large.	1. Cut-in Voltage is quite small.
2. The reverse current is due to minority carriers diffusing to the depletion layer, hence strong temperature dependence.	2. The reverse current is due to the majority carriers that overcome the barrier, hence weak temperature dependence
3. The forward current is due to the minority carrier injection.	3. The forward current is due to majority carrier injection.
4. Switching speed is controlled by recombination of minority injected carriers.	4. Switching speed is controlled by thermalization of hot injected electrons across the barrier.
5. Ideality factor in *I-V* characteristics ~ 1.2-2.0 due to recombination in depletion region	5. Essentially no recombination in depletion region - ideality factor ~ 1.0.

- Heavy doping in the semiconductor causes a very thin depletion width and electron can tunnel across the barrier leading to ohmic behavior. Current is linear in ohmic contact.