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Coimbatore-35
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DEPARTMENT OF ELECTRONICS & COMMUNICATION ENGINEERING

23ECB101 – CIRCUIT ANALYSIS AND DEVICES

I YEAR/ II SEMESTER

UNIT 4 – SEMICONDUCTOR DIODES AND THEIR APPLICATIONS

TOPIC - Depletion and Diffusion Capacitances

Transition or space Charge (or Depletion Region) Capacitance (C_T)

- Under reverse-bias condition, the majority carriers move away from the junction, thereby uncovering more immobile charges.
- Hence, the width of the space-charge layer at the junction *increases with reverse voltage*.
- This increase in uncovered charge with applied voltage may be considered a capacitive effect.
- The parallel layers of oppositely charged immobile ions on the two sides of the junction form the capacitance, C_T, which is expressed as

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

- where dQ is the increase in charge caused by a change in voltage dV. A change in voltage dV in a time dt will result in a current I = dQ/dt given by

$$I = C_T \frac{dV}{dt}$$

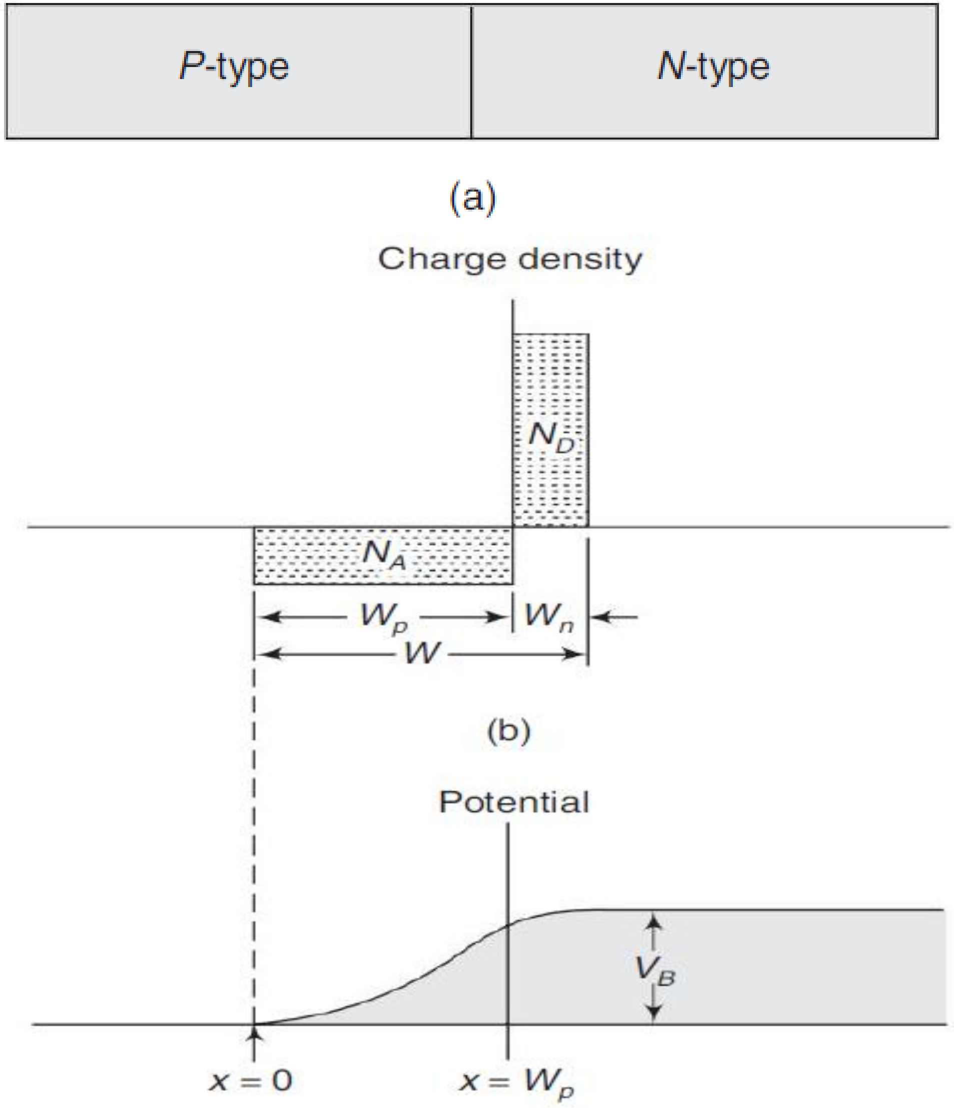
- Therefore, CT is important while considering a diode or a transistor as a circuit element.
- The quantity CT is called *the transition, space-charge, barrier or depletion region capacitance*.

Step-graded Junction

- A PN junction is formed from a single-crystal intrinsic semiconductor by doping part of it with acceptor impurities and the remaining with donors.
- A junction between P-type and N-type materials may be fabricated in a variety of ways.
- The change in impurity concentration from P to N-type semiconductor occurs in a very short length, typically *much less than 1 mm*.
- In an abrupt PN junction, there is a sudden step change from acceptor ions on one side to donor ions on the other side.
- Such a junction is fabricated by placing trivalent indium against N-type germanium and heating the combination to a high temperature for a short time.

Since some of the indium dissolves into the germanium, the N-type germanium is changed into P-type at the junction.

- Such a step-graded junction is called an **alloy, or fusion junction**.
- A step-graded junction is also formed between the emitter and base of an integrated transistor.
- A diffused junction is graded in which case the donor and acceptor concentrations are functions of distance across the junction.
- Then the acceptor density, N_A, gradually decreases and the donor density, N_D, gradually increases till $N_A = N_D$ is reached.
- Therefore, N_D increases and N_A decreases to zero.



Charge density and potential variation at an alloy PN junction

- It is not necessary for the abrupt junction to be symmetrical, that is, the doping concentrations at either side of the junction are dissimilar.
- As shown in Figure, consider a PN diode which is asymmetrically doped at the junction.
- Since the net charge is zero then $qN_AW_p = qN_DW_n$.
- If $N_A >> N_D$ then $W_p << W_n \approx W$. The relationship between potential and charge density is given by the Poisson's equation,

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

egrating the above equation twice,

$$\iint d^2V = \iint \frac{qN_A}{\varepsilon} dx^2$$

Therefore, $$V = \frac{qN_A x^2}{2\varepsilon}$$

At $x = W_p \approx W$, $V = V_B$,

$$V_B = \frac{qN_A W^2}{2\varepsilon}$$

- Here, $V_B = V_0 - V$, where V is a negative number for an applied reverse bias and V_0 is the contact potential.
- Hence, the *width of the depletion layer increases* with applied reverse voltage, i.e., $V_B \alpha W^2$. Therefore, $W \alpha (V_B)^{1/2}$.
- The total charge density of a P-type material with area of the junction A is given by

$$Q = qN_A WA$$

erentiating the above equation w.r.t. V, we get

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

Differentiating w.r.t. V, we get

$$1 = \frac{qN_A\, 2W}{2\varepsilon} \left|\frac{dW}{dV}\right|$$

Therefore, $\left|\dfrac{dW}{dV}\right| = \dfrac{\varepsilon}{qN_A\, W}$

Substituting we get

$$C_T = \left|\frac{dQ}{dV}\right| = AqN_A \frac{\varepsilon}{qN_A\, W}$$

Therefore, $C_T = \dfrac{\varepsilon A}{W}$

Here, e is the permittivity of the material, A the sectional area of the junction and W is the width of the depletion layer over which the ions are uncovered.

- The depletion width, W, is given by

$$W = \left[\frac{2\varepsilon_o \varepsilon_r (V_o - V)}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)\right]^{1/2}$$

where V is the applied voltage and Vo is the barrier potential, or the contact potential.

- When no external voltage is applied, i.e., V = 0, the width of the depletion region of a PN junction diode is of the order of *0.5 microns*.
- The movement of majority carriers across the junction causes opposite charges to be stored at this distance W apart.

This depletion region acts as a dielectric between the two conducting P- and N-regions.

- Therefore, these regions act as a *parallel-plate capacitor* whose transition capacitance C_T is approximately 20 pF with no external bias.
- When a forward bias of +V is applied, the effective barrier potential, VB = [Vo – (+V)], is lowered and hence, the width of the depletion region W decreases and C_T increases.
- Under reverse-bias condition, the majority carriers move away from the junction, thereby uncovering more immobile charges.
- Now the effective barrier potential, VB = [Vo – (–V)], is increased and, hence, W increases with reverse voltage and C_T decreases correspondingly.
- The values of C_T range from *5 to 200 pF*, the larger values being for the high-power diodes.
- This property of voltage variable capacitance with the reverse bias appears in *varactors, vari-caps or voltacaps*.

Diffusion Capacitance (C_D)

- The capacitance that exists in a forward-biased junction is called a **diffusion or storage capacitance** (C_D), whose value is usually much larger than C_T, which exists in a reverse-biased junction.
- This is also defined as the rate of change of injected charge with applied voltage, i.e.,

$$C_D = dQ/dV$$

where dQ represents the change in the number of minority carriers stored outside the depletion region when a change in voltage across the diode, dV, is applied.

Calculation of C_D

Let us assume that the P-material in one side of the diode is heavily doped in comparison with the N-side.

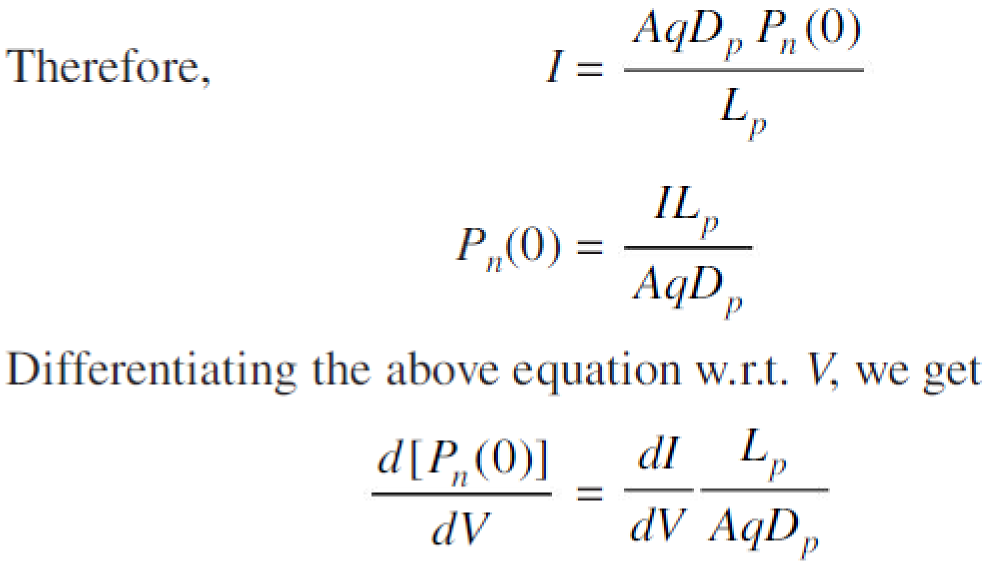
- Since the holes move from the P- to the N-side, the hole current $I \approx I_{pn}(0)$.
- The excess minority charge Q existing on the N-side is given by

$$Q = \int_0^\infty AqP_n(0)\,e^{-x/L_p}\,dx = \left[\frac{AqP_n(0)\,e^{-x/L_p}}{-1/L_p}\right]_0^\infty = L_pAqP_n(0)$$

Differentiating the above equation, we get

$$C_D = \frac{dQ}{dV} = AqL_p\frac{d[P_n(0)]}{dV}$$

- We know that the diffusion hole current in the N-side is Ipn (x) = $A_q D_p P_n(0)/L_p\, e^{-x/Lp}$.
- The hole current crossing the junction into the N-side with x = 0 is



Therefore,
$$I = \frac{AqD_p P_n(0)}{L_p}$$

$$P_n(0) = \frac{IL_p}{AqD_p}$$

Differentiating the above equation w.r.t. V, we get

$$\frac{d[P_n(0)]}{dV} = \frac{dI}{dV}\frac{L_p}{AqD_p}$$

Upon substituting in Eq. (2.14), we have

$$C_D = \frac{dQ}{dV} = \frac{dI\, L_p^2}{dV\, D_p}$$

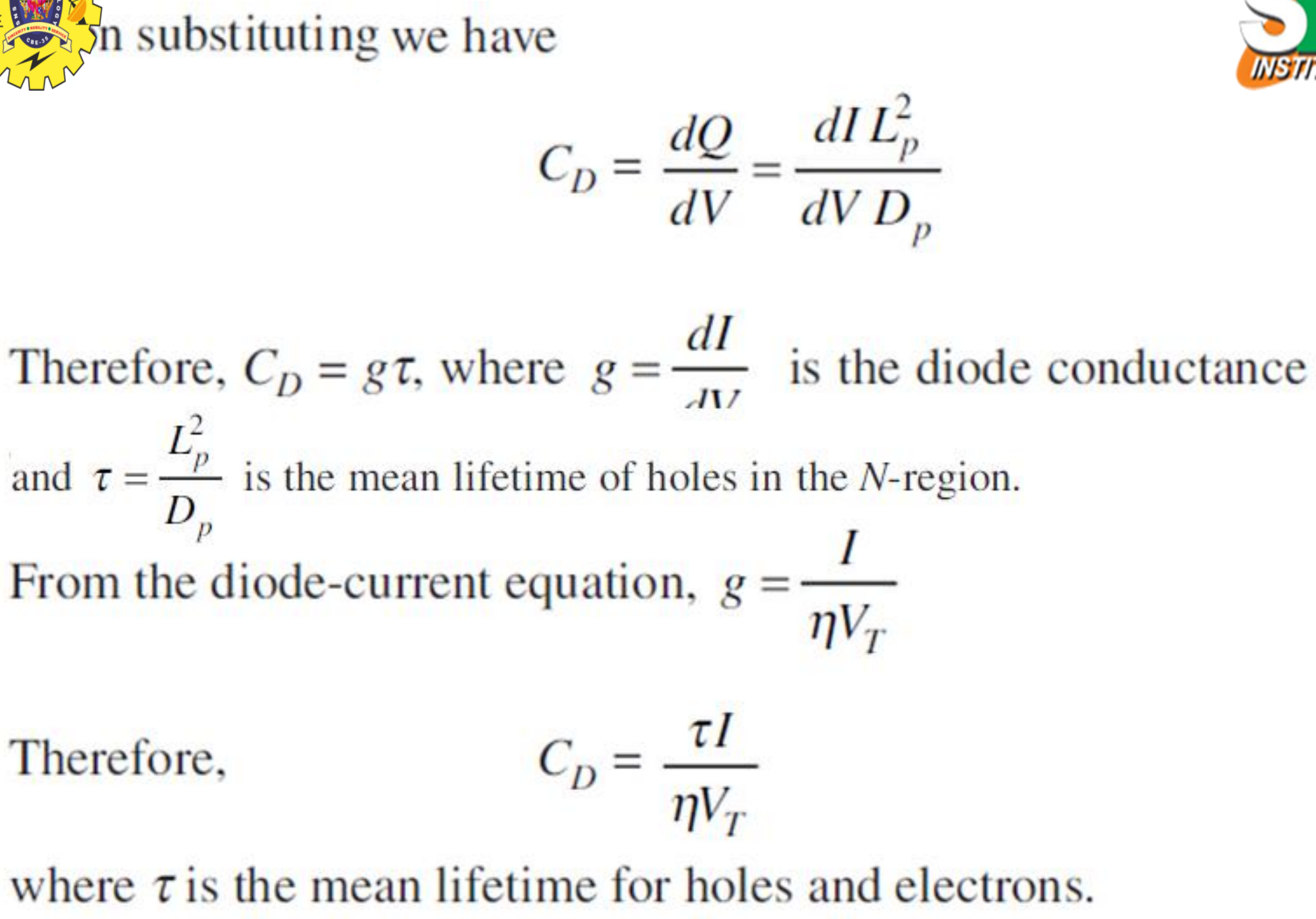
Therefore, $C_D = g\tau$, where $g = \dfrac{dI}{dV}$ is the diode conductance the *N*-region.

From the diode-current equation, $g = \dfrac{I}{\eta V_T}$

Therefore,

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

where τ is the mean lifetime for holes and electrons.



n substituting we have

$$C_D = \frac{dQ}{dV} = \frac{dI\,L_p^2}{dV\,D_p}$$

Therefore, $C_D = g\tau$, where $g = \frac{dI}{dV}$ is the diode conductance

and $\tau = \frac{L_p^2}{D_p}$ is the mean lifetime of holes in the *N*-region.

From the diode-current equation, $g = \frac{I}{\eta V_T}$

Therefore, $$C_D = \frac{\tau I}{\eta V_T}$$

where τ is the mean lifetime for holes and electrons.

- Diffusion capacitance C_D increases exponentially with forward bias or, alternatively, that it is proportional to *diode forward current*, I.
- The values of C_D range from 10 to 1000 pF, the larger values being associated with the diode carrying a larger anode current, I.
- The effect of C_D is negligible for a reverse-biased PN junction.
- As the value of C_D is *inversely proportional to frequency*, it is high at low frequencies and it decreases with the increase in frequency.


THANK YOU