

SEDRA/SMITH
Microelectronic Circuits
SEVENTH EDITION

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Chapter 3

Semiconductors

Introduction

3.1 Intrinsic Semiconductors

3.2 Doped Semiconductors

3.3 Current Flow in Semiconductors

3.4 The pn Junction with an Applied Voltage

3.4.1 Qualitative Description of Junction Operation

3.4.2 The Current-Voltage Relationship of the Junction

3.4.3 Reverse Breakdown

3.5 Capacitive Effects in the pn Junction

2 ways charge can be stored in pn junction.

1. charge in depletion region (more visible when reverse bias)
2. minority charge in n and p material (more visible when forward bias)
 - concentration profile by injecting to n-dope
 - " " " " to p-dope

3.5.1 Depletion or Junction Capacitance

Assumption: pn junction reversed bias with V_R , charge on either side of junction:

$$Q_J = A \sqrt{2\epsilon_s q \frac{N_A N_D}{N_A + N_D} (V_0 + V_R)} = \alpha \sqrt{(V_0 + V_R)} \quad (3.1)$$

We denote α as $A \sqrt{2\epsilon_s q \frac{N_A N_D}{N_A + N_D}}$ and observe that $Q_J \propto \sqrt{V_R}$ (also not linearly related)

- Hard to define capacitance that accounts for changing Q_J when V_R changes

Assumption: junction operates as a point Q and define

$$C_j = \left. \frac{dQ_J}{dV_r} \right|_{V_R=V_Q} \quad (3.2)$$

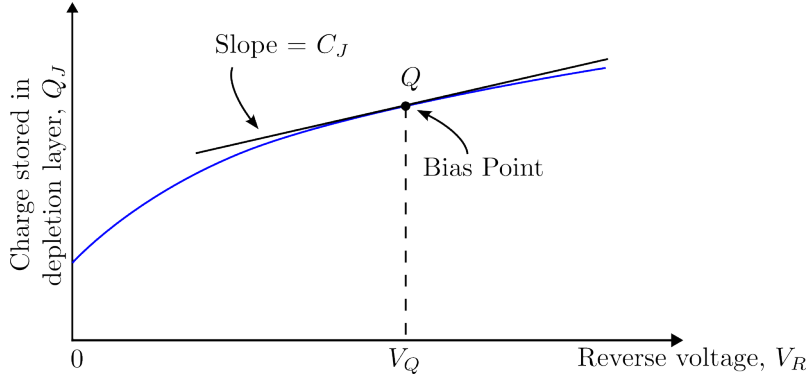


Figure 3.1: The charge stored on either side of the depletion layer as a function of the reverse voltage V_R

Note:-

The definition of capacitance

$$q = CV \implies C = q/V = \frac{\Delta q}{\Delta V}$$

- Equation 3.2 useful in electronic cct design
- This equation used in this book frequently
- Called the “**incremental-capacitance approach**”

Combining equations 3.2 with 3.1 we obtain:

$$C_j = \frac{\alpha}{2\sqrt{V_0 + V_R}} \quad (3.3)$$

We observe that C_j at reverse bias ($V_R = 0$) is $C_{j0} = \frac{\alpha}{2\sqrt{V_0}}$, so we can write C_j as

$$C_j = \frac{C_{j0}}{\sqrt{1 + \frac{V_R}{V_0}}} \quad (3.4)$$

Substituting for α , we obtain:

$$C_j = A \sqrt{\left(\frac{\epsilon_s q}{2}\right) \left(\frac{N_A N_D}{N_A + N_D}\right) \left(\frac{1}{V_0}\right)} \quad (3.5)$$

Before leaving concept of junction capacitance, we introduce

Definition 3.5.1: Terms

Abrupt junction: pn junction, doping concentration changes abruptly at junction boundary (this is deliberately done)

Graded junction: pn junction, carrier concentration changes gradually from one side to another.

If graded junction, then C_j becomes:

$$C_j = \frac{C_{j0}}{\left(1 + \frac{V_R}{V_0}\right)^m}$$

where m is the **Grading coefficient**

- m ranges from 1/3 to 1/2
- m depends on manner in which concentration changes from p to n side

Question 1: Exercise 3.14

For the $pn \dots \text{cm}^2$.

Solution: Solution

3.5.2 Diffusion Capacitance

Consider: pn junction, forward bias:

Assume: in steady state

- Minority-carrier distributions in p and n regions as shown in (Fig. 3.12)
 - Some minority charge carrier charges stored in p and n regions outside depletion region
- Changes in terminal voltage cause charges as mentioned $\uparrow\uparrow$ to change before new steady state

This, completely different charge-storage phenomenon than 3.5.1

- Previous section was charge-storage of non-depletion region
- This section is charge-storage of depletion region

We calculate excess minority-carrier charge (Fig. 3.12) by taking shaded area under exponential

Consider: excess hole charges in n region Q_p

$$\begin{aligned} Q_p &= Aq \times \text{shaded area under the } p_n(x) \text{ curve} \\ &= Aq [p_n(x_n) - p_{n0}] L_p \end{aligned} \quad (3.6)$$

Note:-

Recall area under exponential curve $Ae^{-x/B}$ is equal to AB

Doing some substitutions (add sections) to Eq. (3.6):

$$Q_p = \frac{L_p^2}{D_p} I_p \quad (3.7)$$

We note that the factor $\frac{L_p^2}{D_p}$ relates Q_p to I_p is very useful parameter, and has dimensions of time (s). Thus we denote:

$$\tau_p = \frac{L_p^2}{D_p} \quad (3.8)$$

So:

$$Q_p = \tau_p I_p \quad (3.9)$$

Definition 3.5.2: Terms

Minority-carrier (hole) lifetime: Average time it takes for a hole injected into the n region to recombine with a majority electron, denoted τ_p

This definition has the following implications:

- Entire charge, Q_p disappears
- Q_p has to be replenished every τ_p seconds
- The current responsible for replenishing is I_p

Similarly for electrons charge in p region:

$$Q_n = \tau_n I_n \quad (3.10)$$

Where τ_n is electron lifespan in p region. Thus, the total excess minority-carrier charge:

$$Q = \tau_p I_p + \tau_n I_n \quad (3.11)$$

In terms of $I = I_p + I_n$, the diode current

$$Q = \tau_T I \quad (3.12)$$

Definition 3.5.3: Term

Mean transit time: For the junction, is equal to τ_T

We recognize that one side of junction more heavily doped than another. If $N_A \gg N_D$:

- $I_p \gg I_n$
- $I \approx I_p$
- $Q_p \gg Q_n$
- $Q \approx Q_p$
- $\tau_T \approx \tau_p$

Definition 3.5.4: Term

Incremental diffusion capacitance: Defined C_d , for small changes around a bias point:

$$C_d = \frac{dQ}{dV} = \left(\frac{\tau_T}{V_T} \right) I \quad (3.13)$$

Where I is the forward-bias current

Note:

- $C_d \propto I$
 - Because of this, C_d negligibly small when reverse bias
- To keep C_d small, transit time must be small
 - Important requirement for pn junction for high-speed or high-frequency

Question 2: Exercise 3.15

Use the definition ...

Solution: Solution

Question 3: Exercise 3.16

For the pn ...

Solution: Solution

Chapter 4

Diodes

Introduction

4.1 The Ideal Diode

4.1.1 Current-Voltage Characteristic

- Diodes are the most simple and fundamental non-linear CCT
- Similar to resistor: 2 terminals
- Dissimilar to resistor: nonlinear $i - v$

Roadmap:

1. Ideal diode
2. Silicon junction diode
 - (a) Terminal characteristics
 - (b) Analysis diode CCT
3. Device modelling
4. Rectifiers
5. Photodiodes and LEDs
6.

Diode is nothing more than a pn -junction

4.2 The Ideal Diode

