NANYANG TECHNOLOGICAL UNIVERSITY

Course: EE3013 Semiconductor Devices and Processing

School: School of Electrical and Electronic Engineering

Week 13 – Part I - Revision

Part 1 - Revision

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Week 1 - PN Junction Diodes

P- and N-type Semiconductors

p-type silicon

Doped by acceptors (Boron)

Majority carriers

$$p = N_A = n_i e^{\frac{E_1 - E_F}{kT}}$$

Minority carriers

$$n = \frac{n_i^2}{N_A} \quad \text{where } p \gg n$$

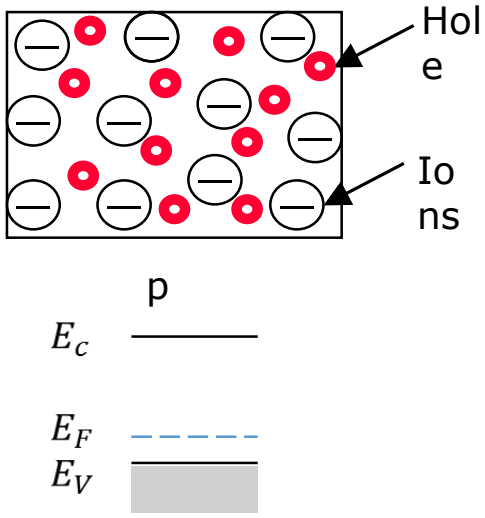

Figure 7.1(a)

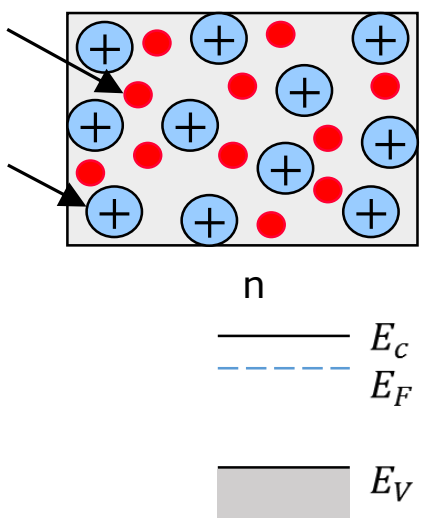

Figure 7.1(b)

n-type silicon

Doped by donors (Phosphorus)

Majority carriers

$$n = N_D = n_i e^{\frac{E_F - E_i}{kT}}$$

Minority carriers

$$p = \frac{n_i^2}{N_D} \quad \text{where } n \gg p$$

Holes flow from left to right

Hole current density *J_p to right*

$$J_p = -qD_p \frac{dp}{dx}$$

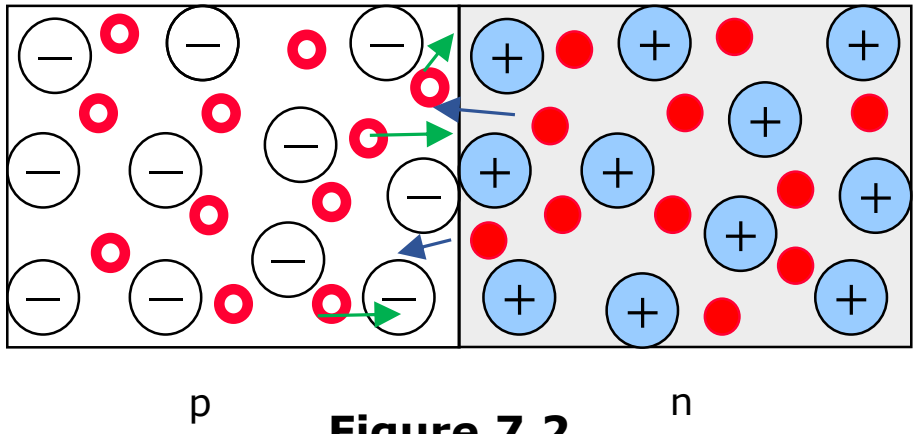

Figure 7.2

Electrons flow to left

But electron current density ***J_n***

$$J_n = qD_n \frac{dn}{dx}$$

PN Junction Formation

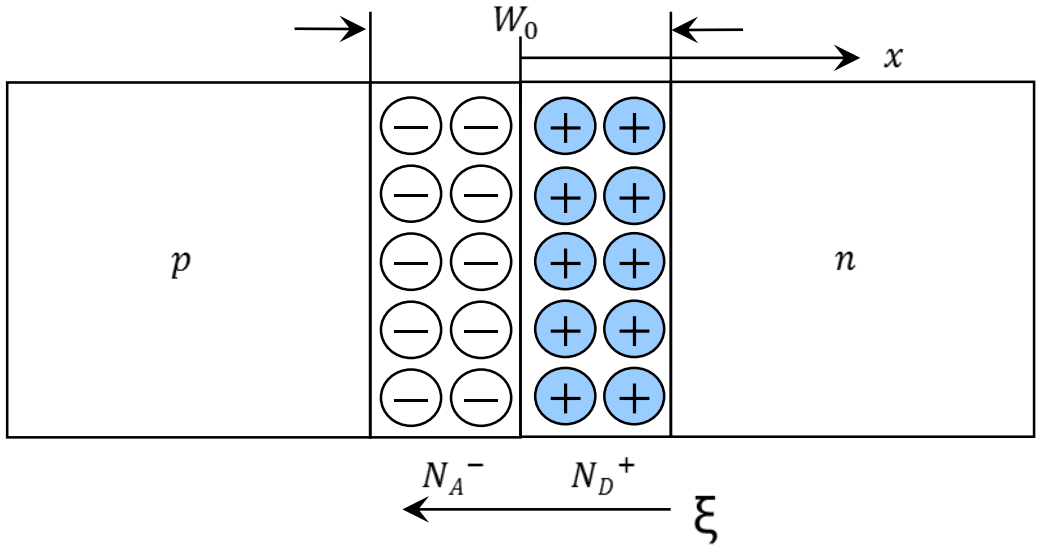

Figure 7.3

- As holes leave the p-side, some negative acceptor ions (***N_A^-***) near the junction are left uncompensated (since the acceptors are fixed in the semiconductor lattice while the holes are immobile).
- Similarly, some positive donor ions (***N_D^+***) are left as electrons leave n-side.
- Negative and positive space charges form a depletion region.
- They create an **electrical field,** ξ, directed from positive charges towards negative charges.

PN Junction Formation (Cont'd.)

At thermal equilibrium, (that is, the steady-state condition at a given temperature without any external excitation), the net electron and hole currents flowing across the junction are zero.

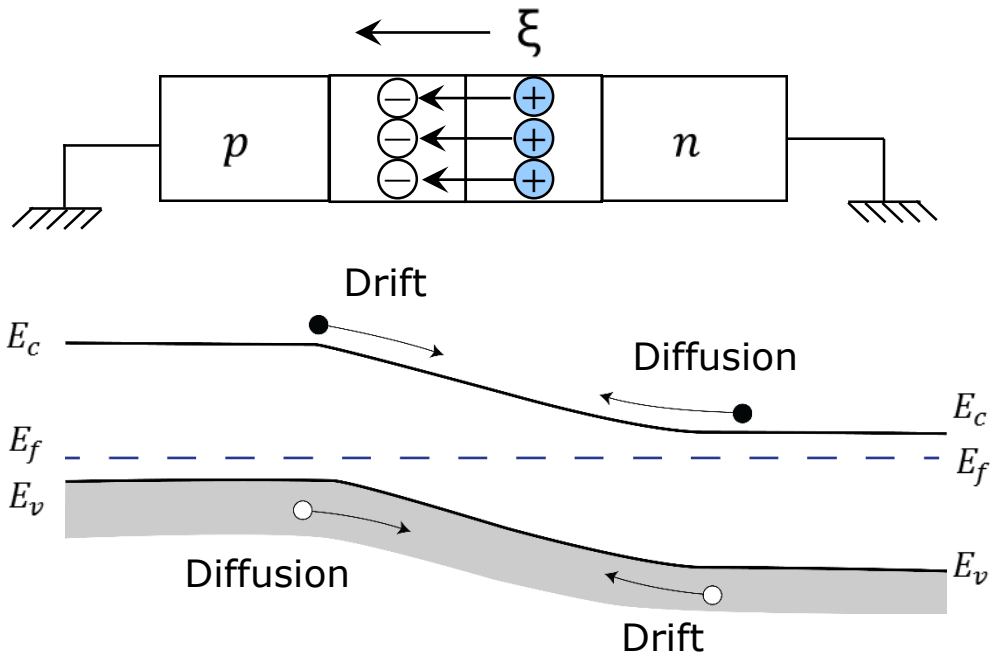

Figure 7.4

$$J_n(drift) = J_n(diffusion)$$

$$J_p(drift) = J_p(diffusion)$$

$$J_p = q\mu_p p\xi - qD_p \frac{dp}{dx} = 0 \quad \textit{(Equation 7.1)}$$

$$J_n = q\mu_n n\xi + qD_n \frac{dn}{dx} = 0 \quad \textit{(Equation 7.2)}$$

$$J = J_n + J_p = 0$$

PN Junction Formation (Cont'd.)

(1) Built-in Potential V_{bi}

$$\Psi_p \equiv -\frac{1}{q}(E_i - E_F)|\, x \le -x_p = -\frac{kT}{q}\ln\frac{N_A}{n_i}$$

$$\Psi_n \equiv -\frac{1}{q}(E_i - E_F)|\, x \ge x_n = \frac{kT}{q}\ln\frac{N_D}{n_i}$$

$$V_{bi} = \Psi_n - \Psi_p = \frac{kT}{q}\ln\frac{N_A N_D}{n_i^2}$$ *(Equation 7.3)*

(2) Space charge neutrality

$$N_A x_p = N_D x_n$$ *(Equation 7.4)*

(3) Total depletion layer width

$$W = x_p + x_n = \sqrt{\frac{2\varepsilon_s}{q}\left[\frac{N_A + N_D}{N_A N_D}\right]V_{bi}}$$ *(Equation 7.5)*

(4) Maximum electric field ξ_m at $x = 0$

$$\xi_m = \frac{qN_D x_n}{\varepsilon_S} = \frac{qN_A{}^x p}{\varepsilon_S}$$ *(Equation 7.6)*

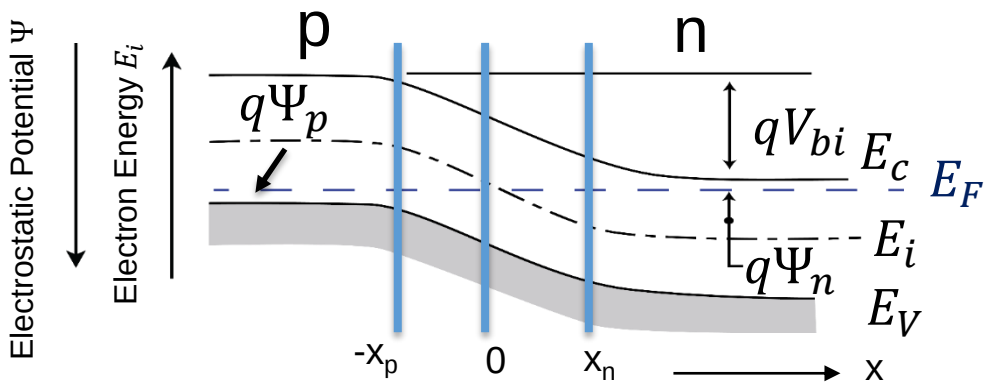

Figure 7.5

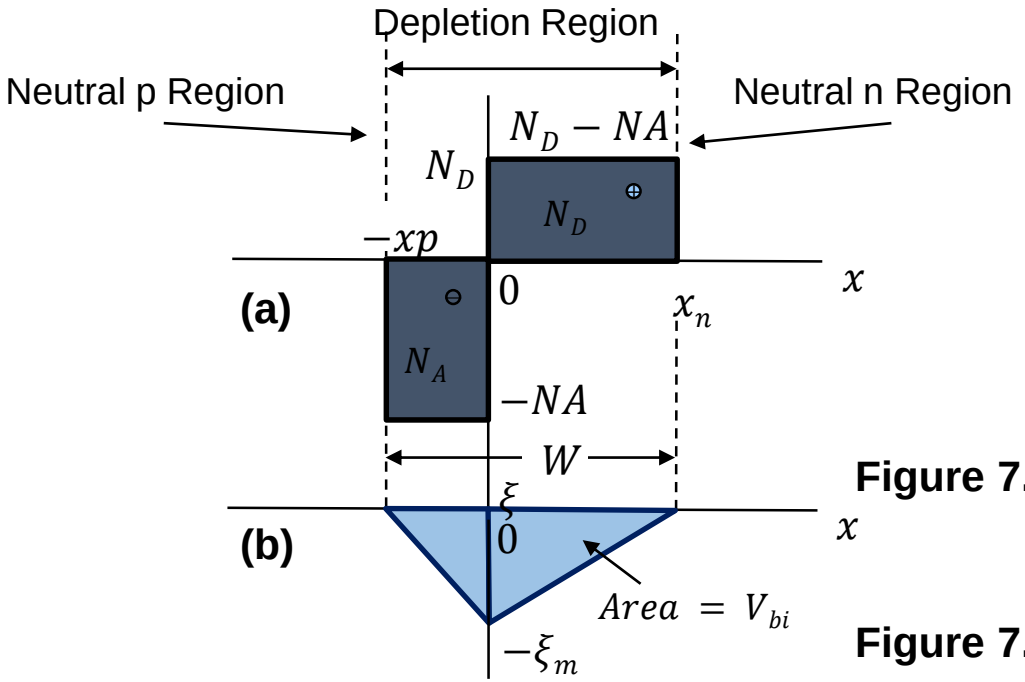

Figure 7.6

Figure 7.7

P-N Junction under Bias

Forward bias (V_F):

- Depletion layer width becomes smaller.

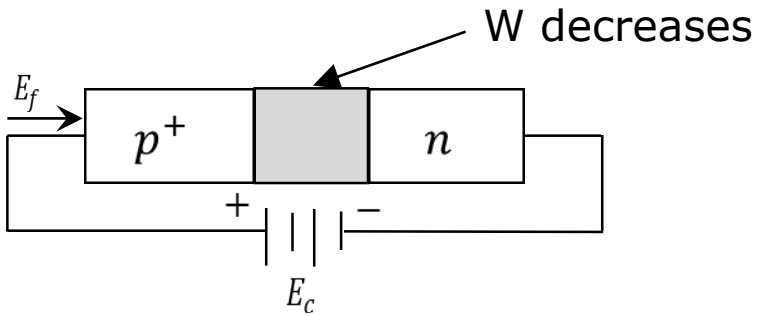

Figure 7.7 (a)

- The total electrostatic potential becomes $V_{bi}-V_F$.

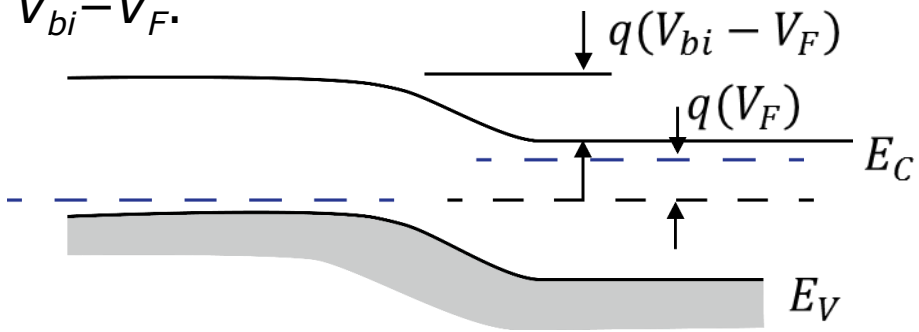

Figure 7.7 (b)

Reverse bias (V_R):

- Depletion layer width increased.

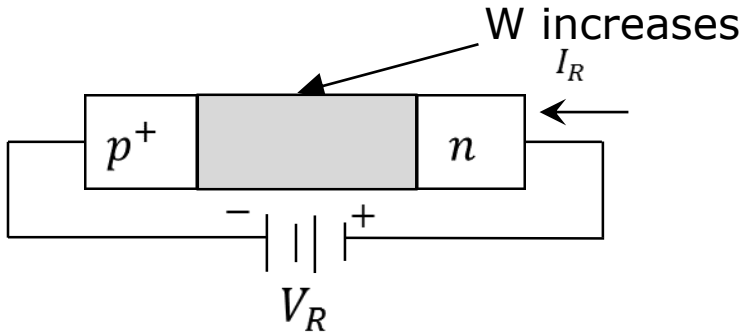

Figure 7.8 (a)

- The total electrostatic potential becomes $V_{bi} + V_R$.

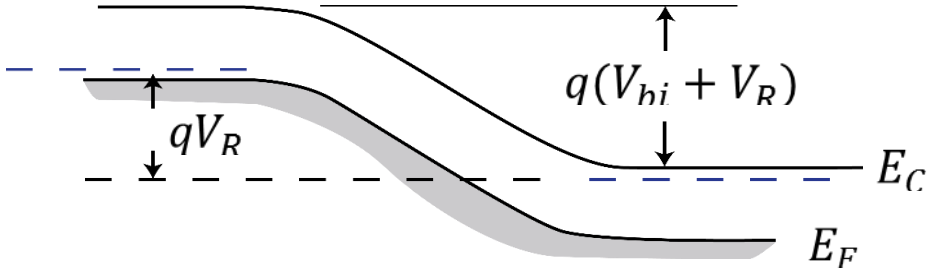

Figure 7.8 (b)

$$W_{RB} = \sqrt{\frac{2\varepsilon_s}{q}\left[\frac{N_A+N_D}{N_A N_D}\right](V_{bi}+|V_R|)}$$ *(Equation 7.7)*

Injected Minority Electron and Hole Concentrations and Current Distributions

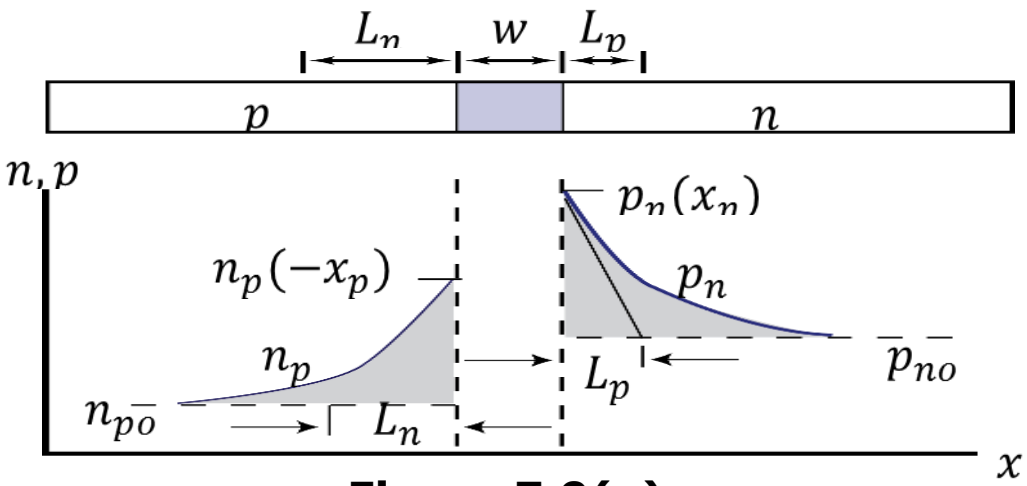

Figure 7.9(a)

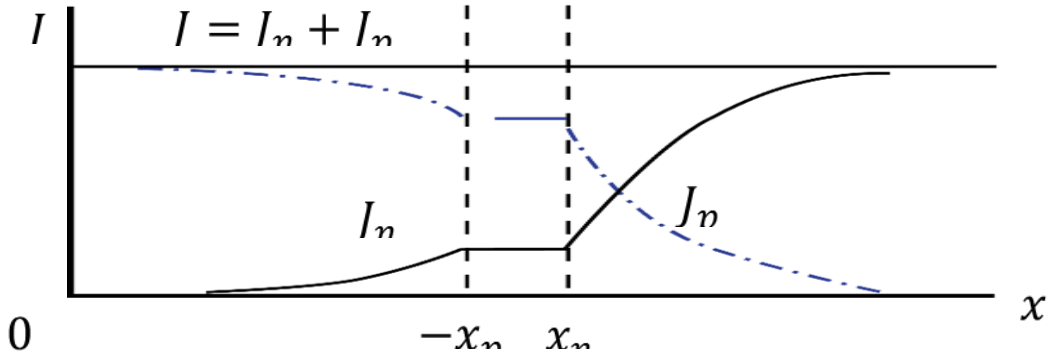

Figure 7.9(b)

Forward bias

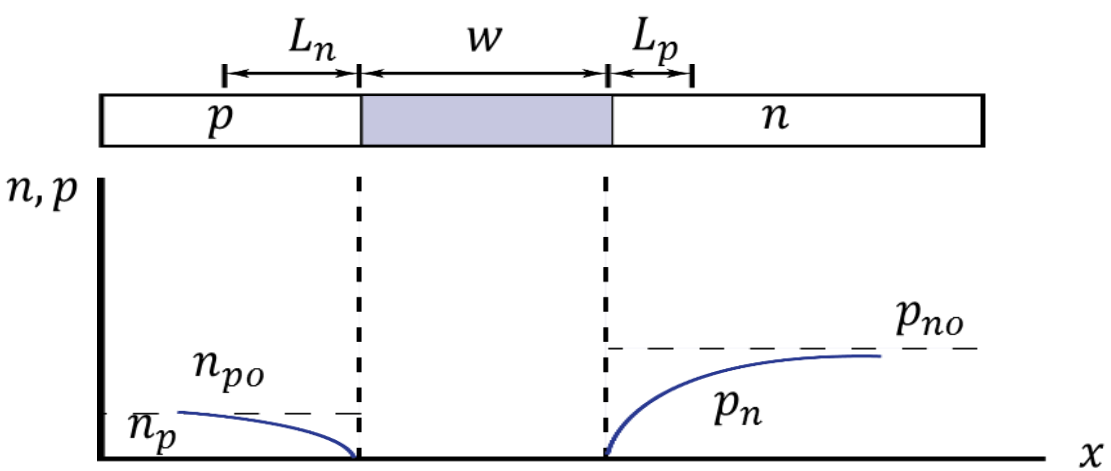

Figure 7.10(a)

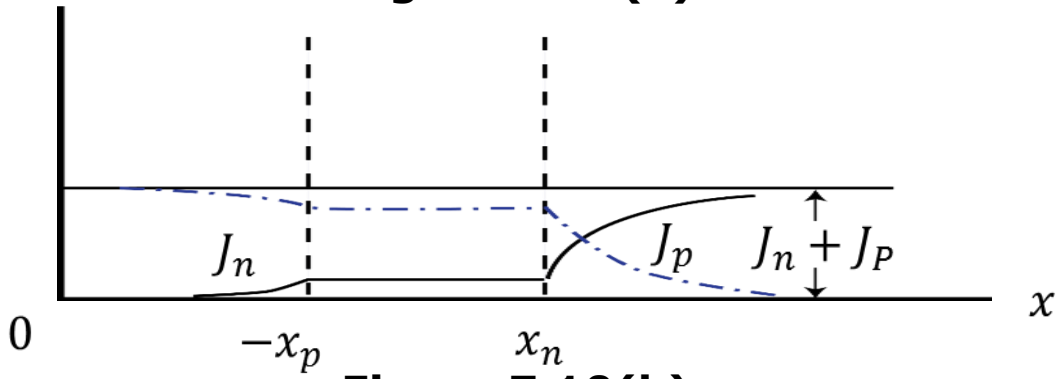

Figure 7.10(b)

Reverse bias

Total current density: $J = J_n(-x_p) + J_p(x_n) = \left(\frac{qD_p p_{no}}{L_p} + \frac{qD_p n_{po}}{L_n}\right)\left[e^{qV_F/kT} - 1\right]$ *(Equation 7.8)*

Depletion Capacitance

For one-sided abrupt junction, the depletion capacitance per unit area is:

$$C_j = \frac{\varepsilon_s}{W} = \sqrt{\frac{q\varepsilon_s N_B}{2(V_{bi} - V)}}$$ *(Equation 7.9)*

Or

$$\frac{1}{C_j{}^2} = \frac{2(V_{bi} - V)}{q\varepsilon_s N_B}$$ *(Equation 7.10)*

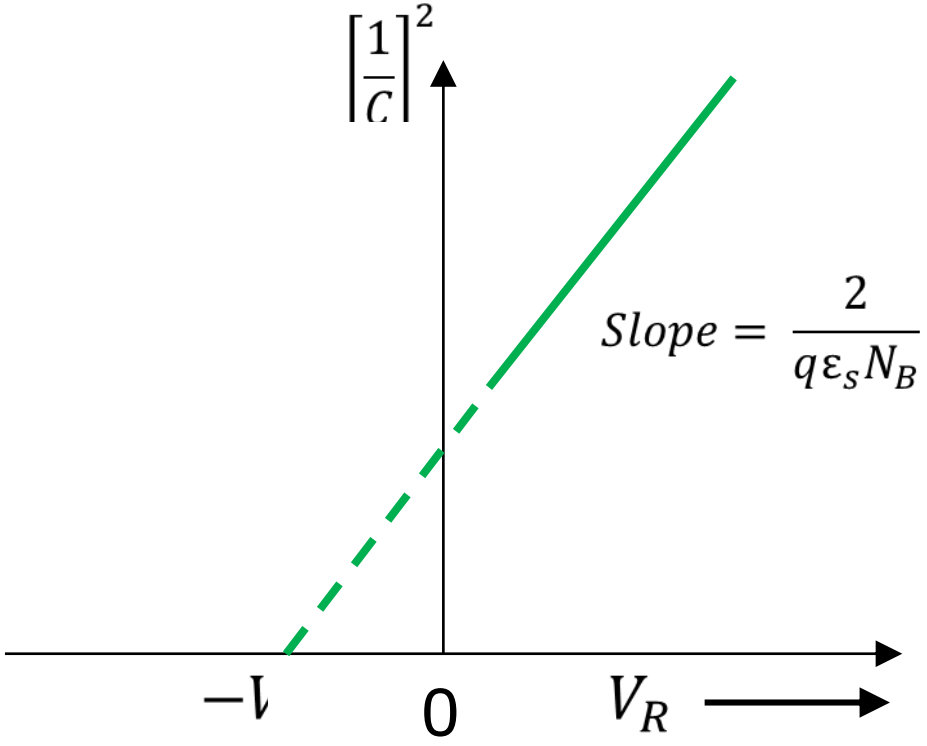

Figure 7.11

Problem 1

Question:

Consider a uniformly doped Si pn junction at T=300K. The junction capacitance at zero bias is $C_j(0V)$ and the junction capacitance with a 10V reverse-biased voltage is $C_j(-10V)$. The ratio of the capacitances is:

$$\frac{C_j(0V)}{C_j(-10V)} = 3.13$$

Also under reverse bias, the space charge width into the p region is 0.2 of the total space charge width:

i. Determine the built-in potential V_{bi}.

ii. Determine the acceptor (N_a) and donor (N_d) concentrations.

Problem 1 (Cont'd.)

Solution:

i. We have $\frac{C'_j(0)}{C'_j(10)} = \frac{\left[\frac{\epsilon_s N_a N_d}{2(V_{bi})(N_a+N_d)}\right]^{\frac{1}{2}}}{\left[\frac{\epsilon_s N_a N_d}{2(V_{bi}+V_R)(N_a+N_d)}\right]^{\frac{1}{2}}}$ or $\frac{C'_j(0)}{C'_j(10)} = 3.13 = \left(\frac{V_{bi}+V_R}{V_{bi}}\right)^{\frac{1}{2}}$

For $V_R = 10V$, we find: $(3.13)^2 V_{bi} = V_{bi} + 10$ or $V_{bi} = 1.137V$

ii. $x_p = 0.2W = 0.2(x_p + x_n)$ then $\frac{x_p}{x_n} = 0.25 = \frac{N_d}{N_a}$

Now, $V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)$ so $1.137 = (0.0259)\ln\left[\frac{0.25 N_a^2}{(1.8\times10^6)^2}\right]$ $N_a = \frac{1.8\times10^6}{\sqrt{0.25}} \exp\left[\frac{1.137}{2(0.0259)}\right]$

Which yields $N_a = 1.23 \times 10^{16}\text{cm}^{-3}$ and $N_d = 3.07 \times 10^{15}\text{cm}^{-3}$

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Week 2 - Bipolar Junction Transistors

A p-n-p Transistor at Thermal Equilibrium

(a) A *p-n-p* transistor with no external voltage applied (thermal equilibrium).

W_{eb} and W_{bc} are the depletion regions of the E-B and B-C junctions, respectively.

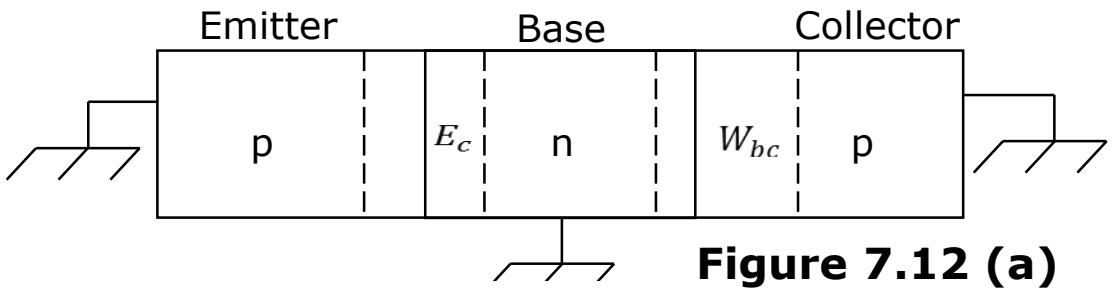


Figure 7.12 (a)

(b) Doping profile of the transistor with abrupt impurity distributions in three regions.

N_A(emitter)> N_D(base)> N_A(collector).

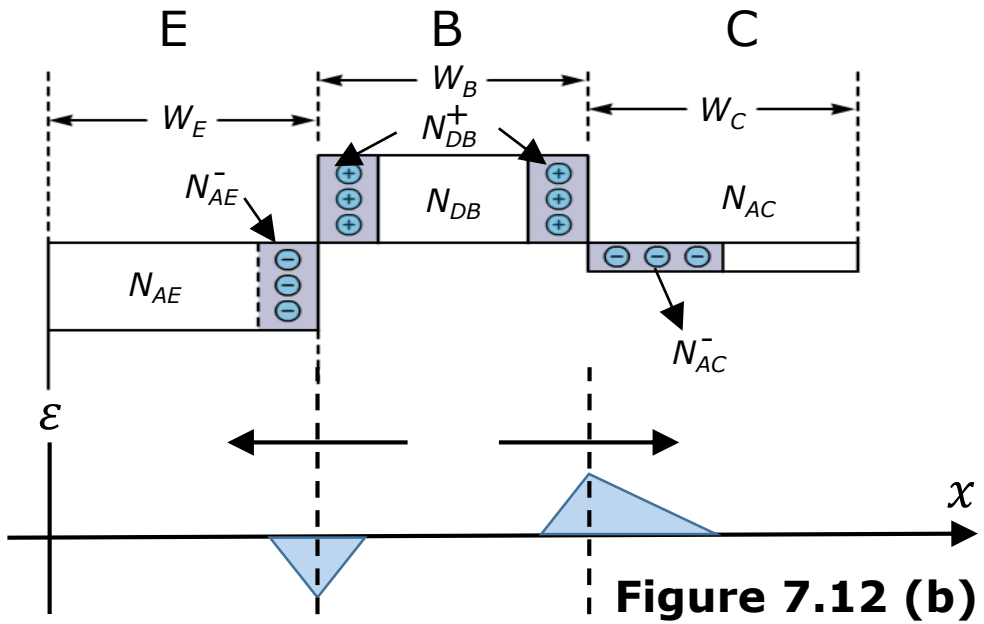


Figure 7.12 (b)

(c) Electric-field profile.

(d) Energy band diagram at thermal equilibrium.

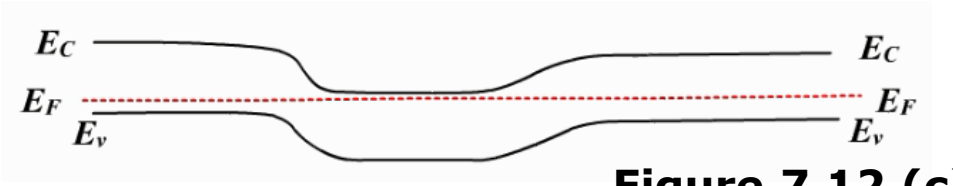


Figure 7.12 (c)

A p-n-p Transistor Under Active Mode

(a) **<u>Active mode</u>**:

- Emitter-base junction is forward biased.
- Base-collector junction is reverse biased.
- W_{eb} is decreased; W_{bc} is increased.

(b) Less +ve and –ve charges in W_{eb} and more in W_{bc}.

(c) Electric-field: enhanced in B-C junction but decreased in E-B junction.

(d) Energy bands move up in collector and down in emitter.

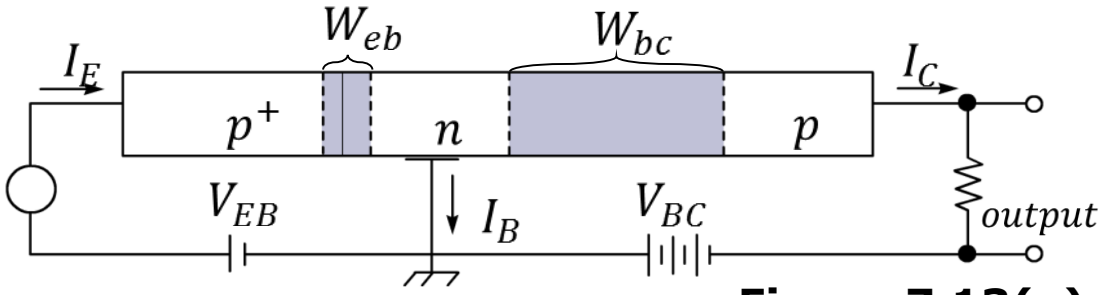


Figure 7.13(a)

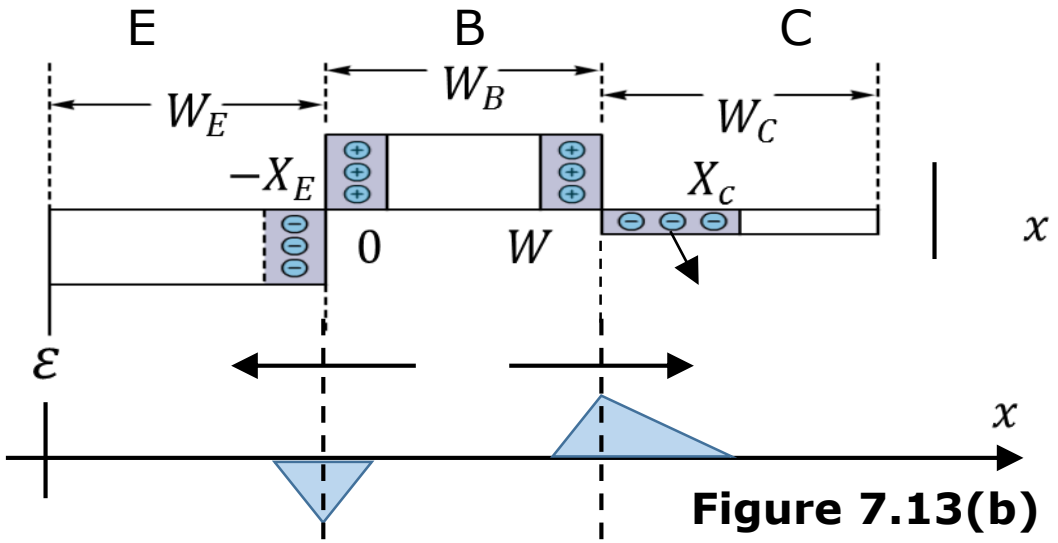


Figure 7.13(b)

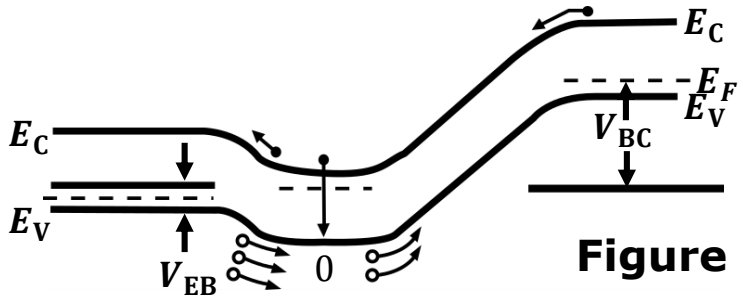
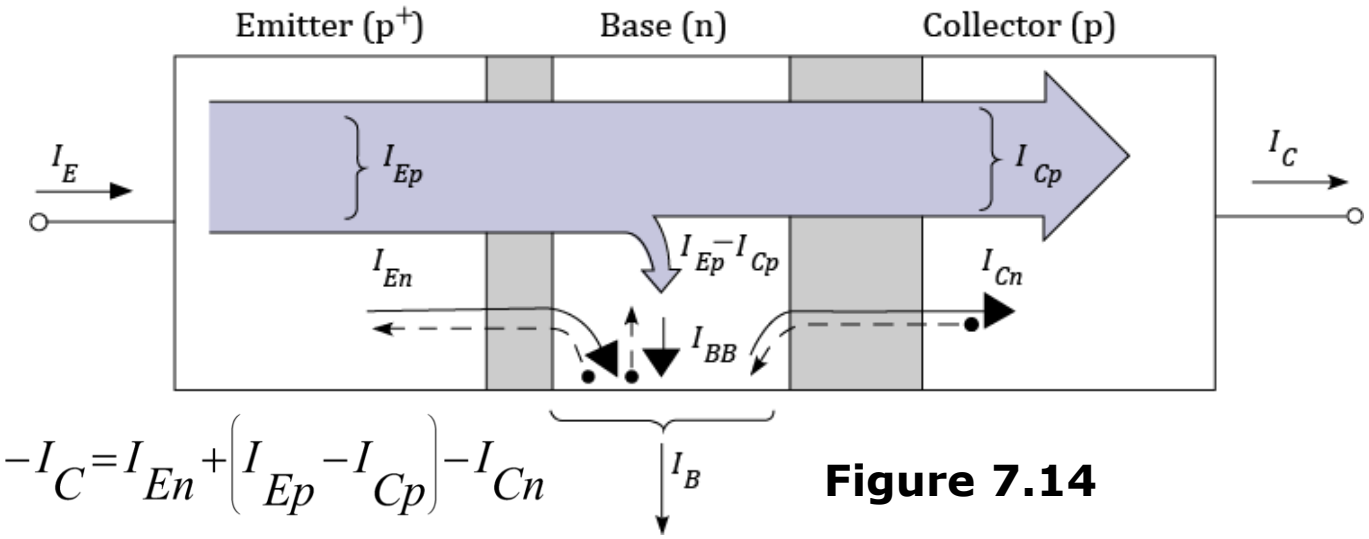


Figure 7.13(c)

Transistor Current Relations

$$I_E = I_{Ep} + I_{En}$$



$$I_C = I_{Cp} + I_{Cn}$$

$$I_B = I_E - I_C = I_{En} + \left(I_{Ep} - I_{Cp}\right) - I_{Cn}$$

Figure 7.14

I_{Ep}: The current of holes injected from the emitter, which is the largest current component.

I_{En}: The current of electrons being injected from the base to the emitter (which is not desirable).

I_{Cp}: The current of the injected holes which are collected by the collector.

I_{Cn}: The current corresponding to thermally generated electrons that are near the *B-C* junction edge and are drifted from the collector to the base.

I_{BB}: The current due to the electrons which recombine with some of the injected holes (i.e., $I_{BB} = I_{Ep} - I_{Cp}$)

Current Components in BJT

- **Recall:** hole and electron diffusion currents:

$$\left.\begin{aligned} J_h(diff) &= -qD_h \frac{dp}{dx}, \\ J_e(diff) &= qD_e \frac{dn}{dx} \end{aligned}\right\} \quad \textit{(Equation 7.11)}$$

- To determine the currents in a BJT, we just need to find out the carrier distributions.
- The currents are then calculated by:

$$I_{Ep} = A\left(-qD_p \frac{dp}{dx}\bigg|_{x=0}\right)$$

$$I_{En} = A\left[qD_{En} \frac{dn_E}{dx}\bigg|_{x=-x_E}\right]$$

$$I_{Cp} = A\left[-qD_p \frac{dp}{dx}\bigg|_{x=W}\right]$$

$$I_{Cn} = A\left(qD_{Cn} \frac{dn_C}{dx}\bigg|_{x=x_C}\right)$$

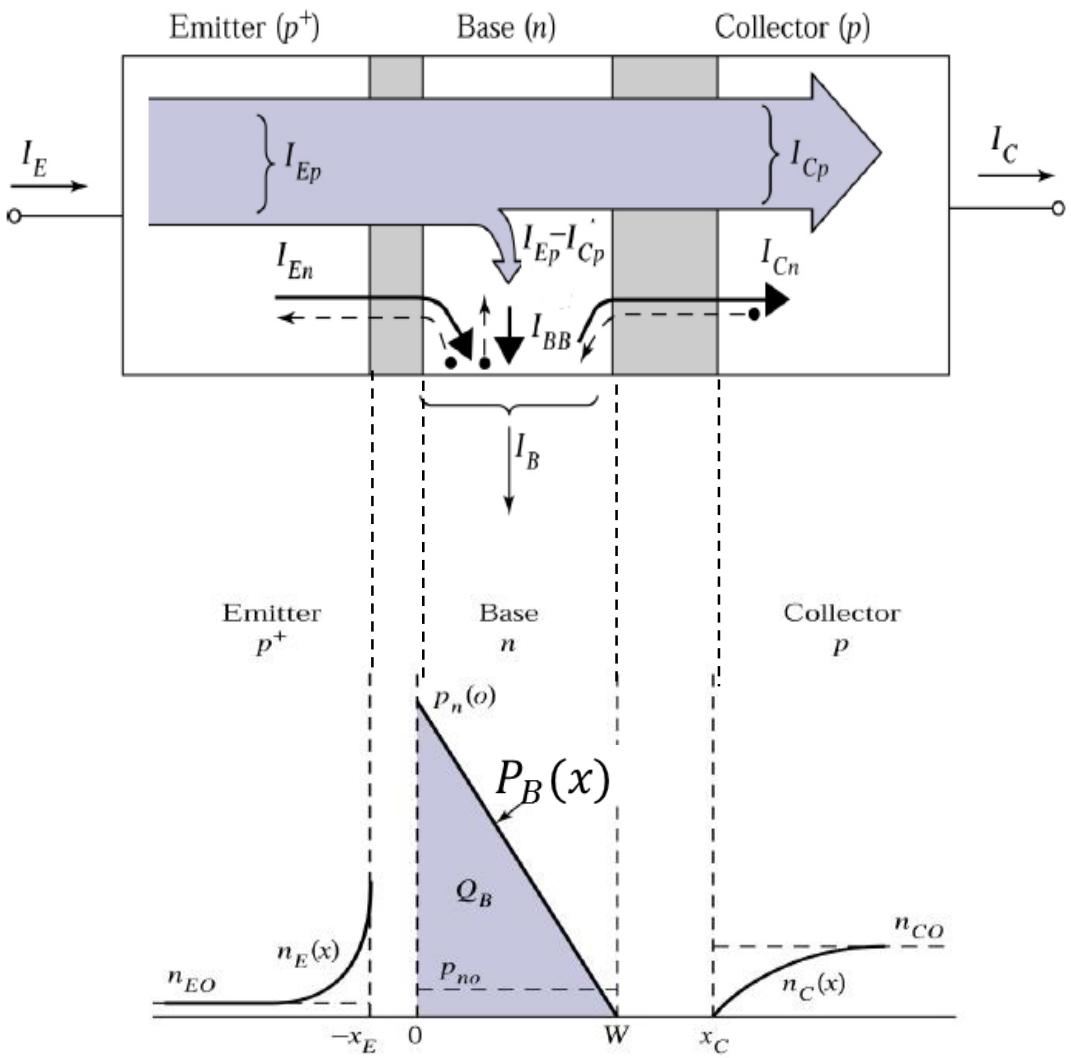


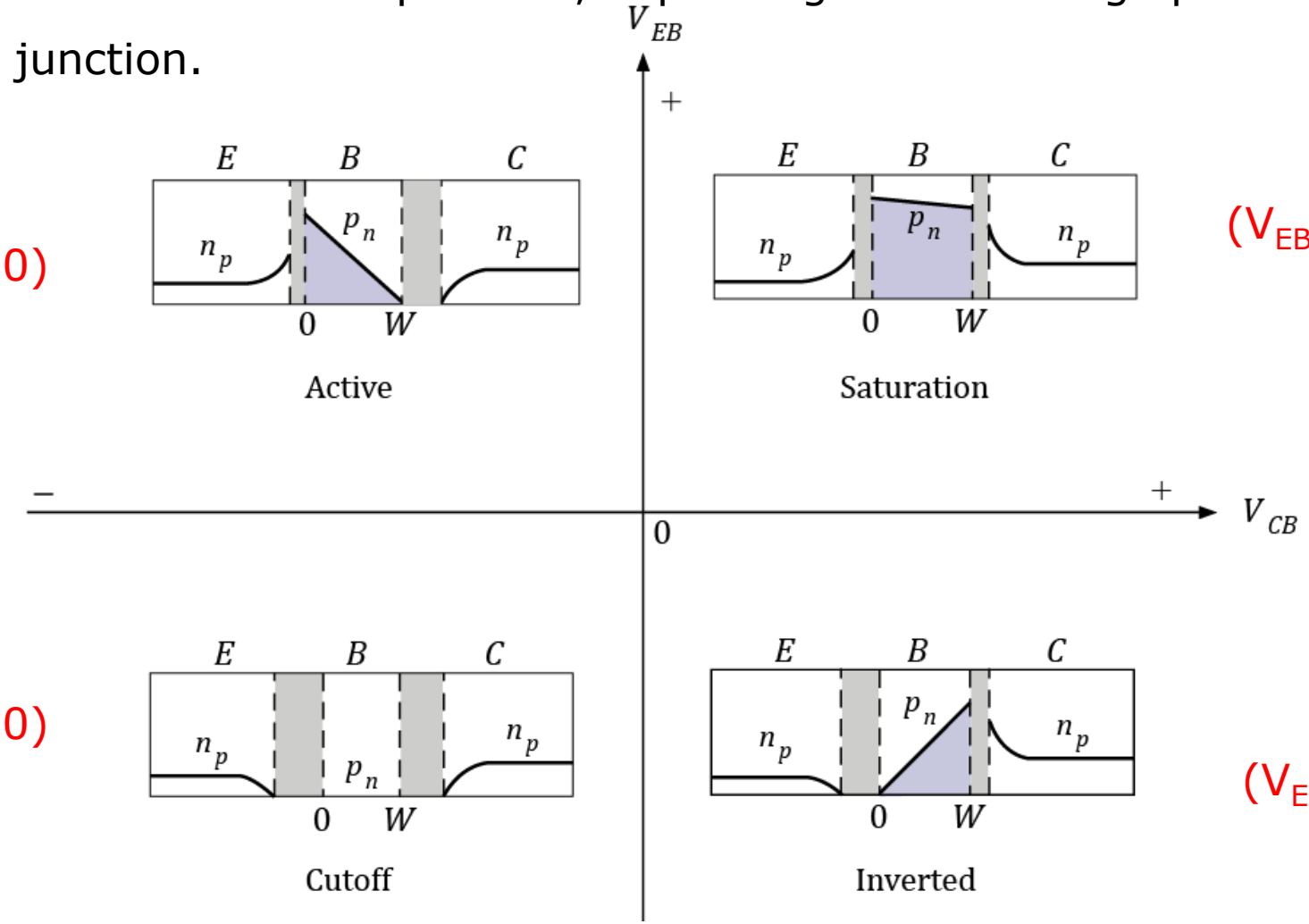
Figure 7.15

Modes of Operation

A bipolar transistor has our modes of operation, depending on the voltage polarities on the E-B junction and the B-C junction.

(V_{EB}>0 and V_{CB}<0)

(V_{EB}>0 and V_{CB}>0)



(V_{EB}<0 and V_{CB}<0)

(V_{EB}<0 and V_{CB}>0)

Figure 2.21

(1) Common-Base Configuration

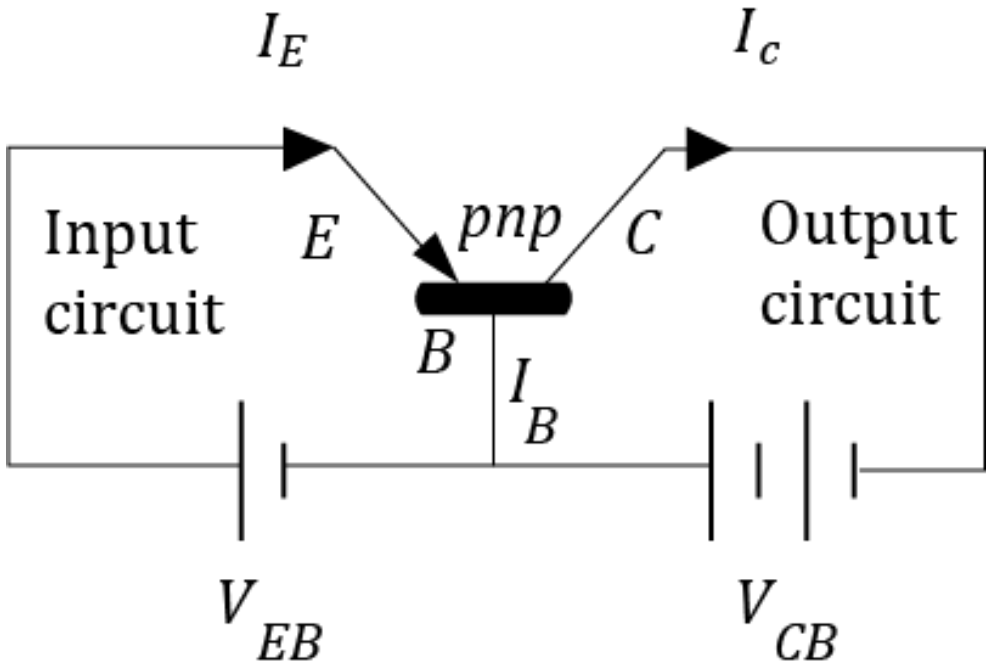


Figure 7.16

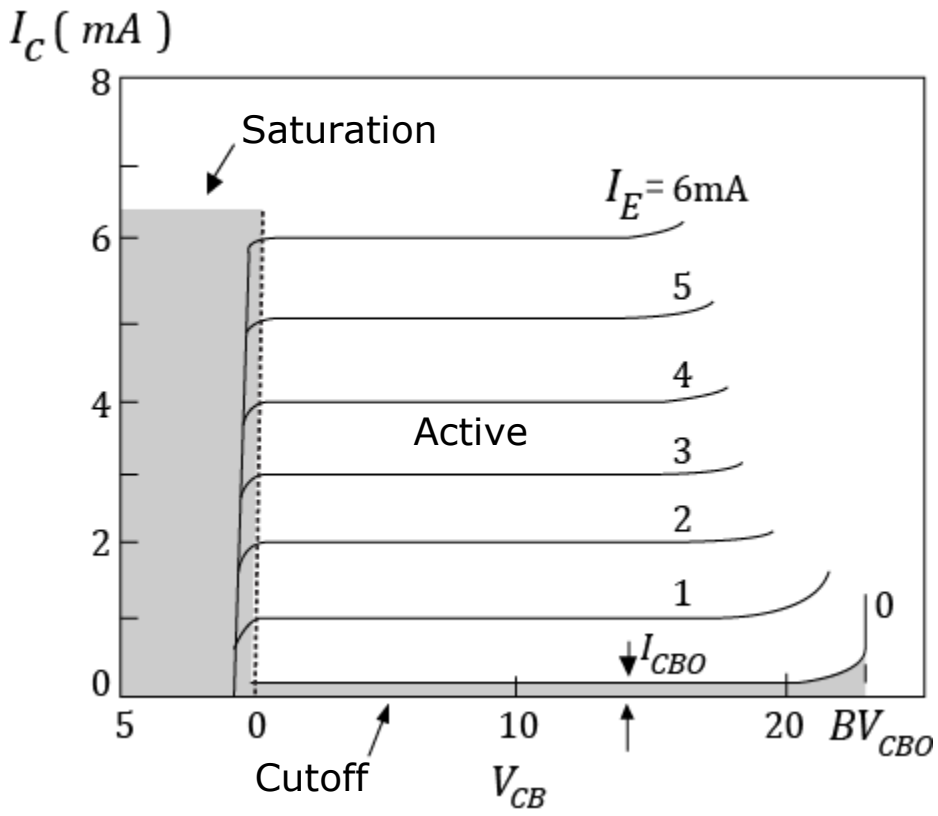


Figure 7.17

$$\alpha_0 \equiv \frac{I_{CP}}{I_E} = \left[\frac{I_{Ep}}{I_{Ep} + I_{En}}\right]\left[\frac{I_{Cp}}{I_{Ep}}\right] \quad \textit{(Equation 7.12)}$$

Emitter efficiency γ *Base transport factor* α_T,

$$\alpha_0 = \gamma\alpha_T \quad \textit{(Equation 7.13)}$$

(2) Common-Emitter Configuration

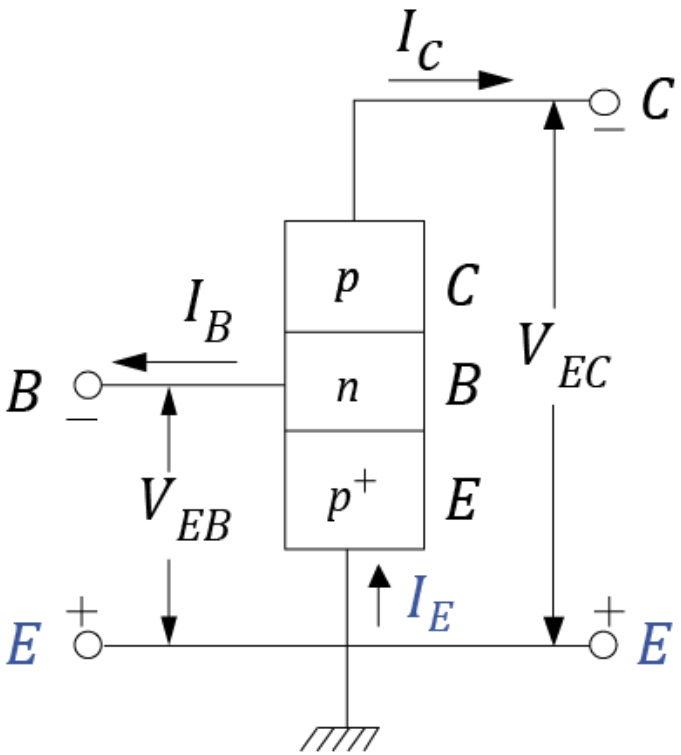


Figure 7.18

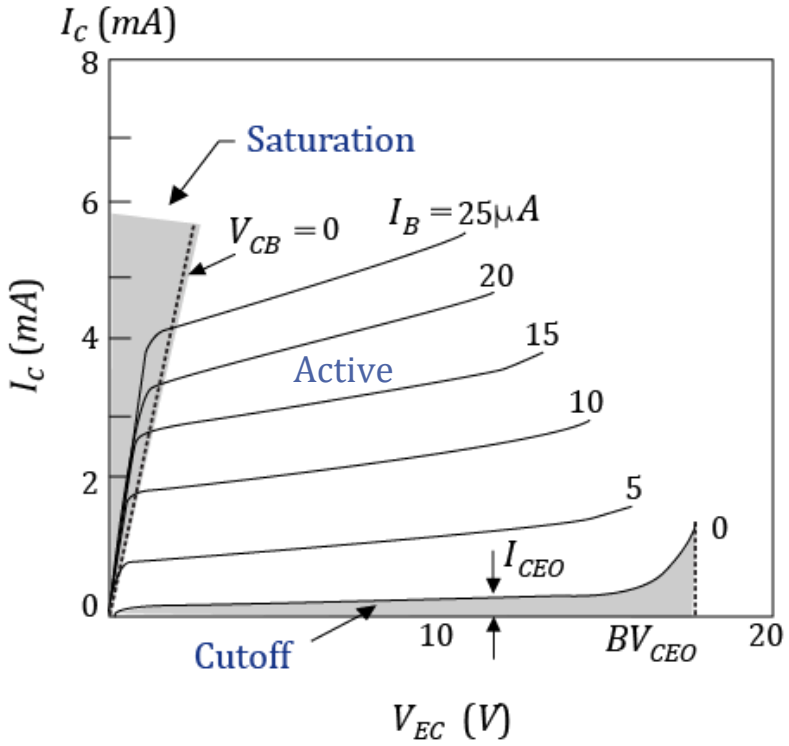


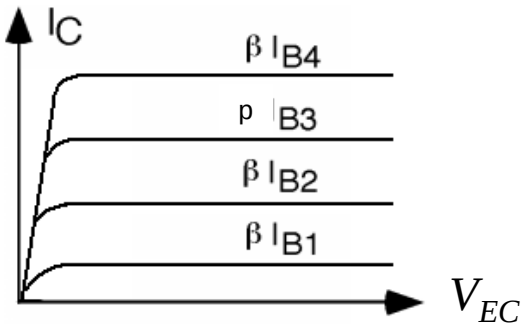
Figure 7.19

Common-emitter gain:

$$\beta_0 = \frac{\Delta I_C}{\Delta I_B} = \frac{\alpha_o}{1 - \alpha_o}$$

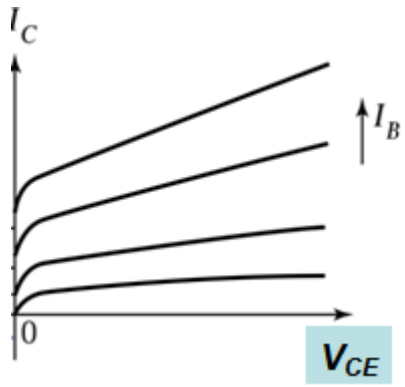
(Equation 7.13)

Base Width Modulation



I-V of ideal BJTs

Figure 7.20



I-V of practical BJTs

Figure 7.21

- As the reverse bias to the B-C junction increases, the neutral base width decreases.
- The reduced base width will cause the gradient to **increase**.
- The increased gradient in the minority-carrier concentration causes an increase in diffusion current I_C and hence β.

Early Voltage

The extensions of collector currents for different base currents will meet at $-V_A$.

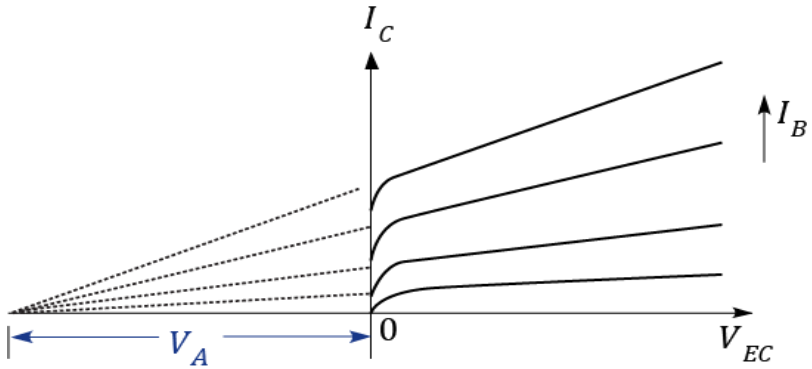


Figure 7.22

$$I_C = g_0(V_{EC} + V_A) \quad \textit{(Equation 7.14)}$$

Cut-off Frequency of BJT

- The current gain is a constant at low frequencies.
- However, it will decrease after a critical frequency is reached.

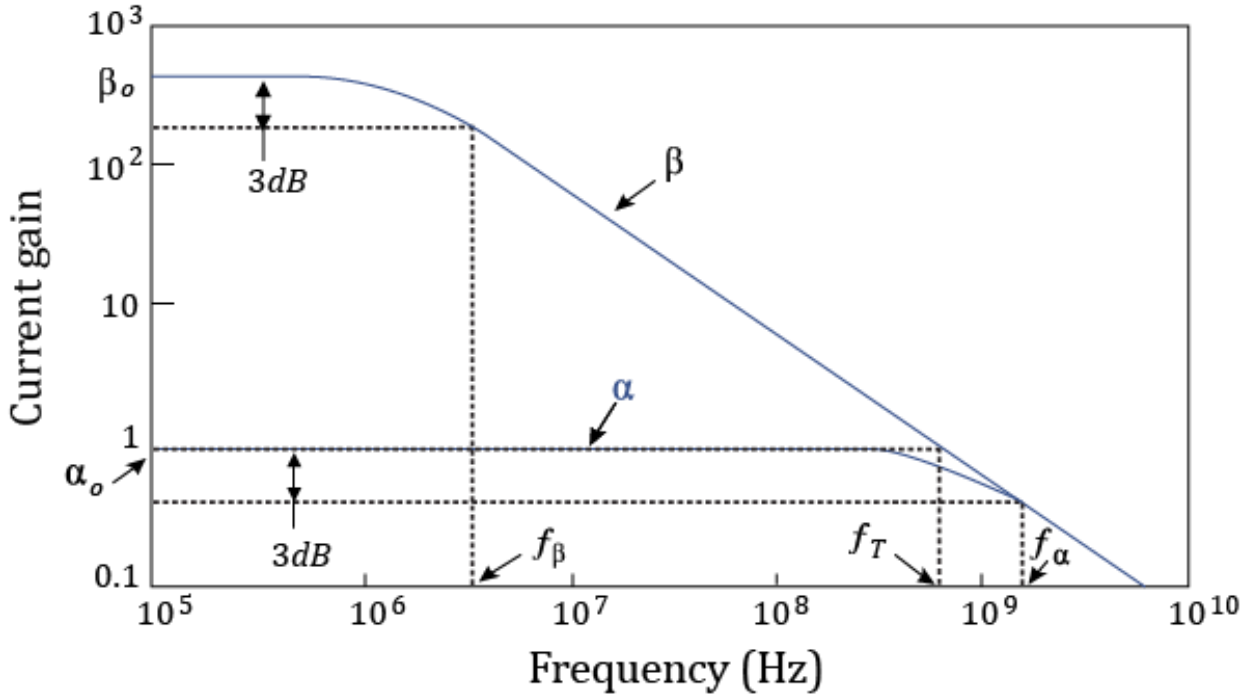


Figure 7.23

f_a: Common-base cut-off frequency

f_β: Common-emitter cut-off frequency

f_T: Cut-off frequency

$$\tau_T \approx \tau_B = \frac{W^2}{2D_p} \text{ and } f_T \approx \frac{1}{2\pi\tau_B} = \frac{D_P}{\pi W^2}$$

Problem 2

Question:

A uniformly doped silicon npn bipolar transistor at T=300K is biased in the forward-active mode.

The doping concentration are N_E = 8 x $10^{17}\mathrm{cm}^{-3}$. N_B = 2 x $10^{16}\mathrm{cm}^{-3}$. N_C = 1 x $10^{15}\mathrm{cm}^{-3}$.

i. Sketch the minority carrier distribution in the emitter, base and collector regions of the bipolar transistor.

ii. For V_{BE} = 0.64V, find the minority carrier concentrations (n_p) at the two space charge edges in the base.

iii. Explain how one can design the BJT to improve the emitter efficiency and the base transport.

Problem 2 (Cont'd.)

Solution:

(i)

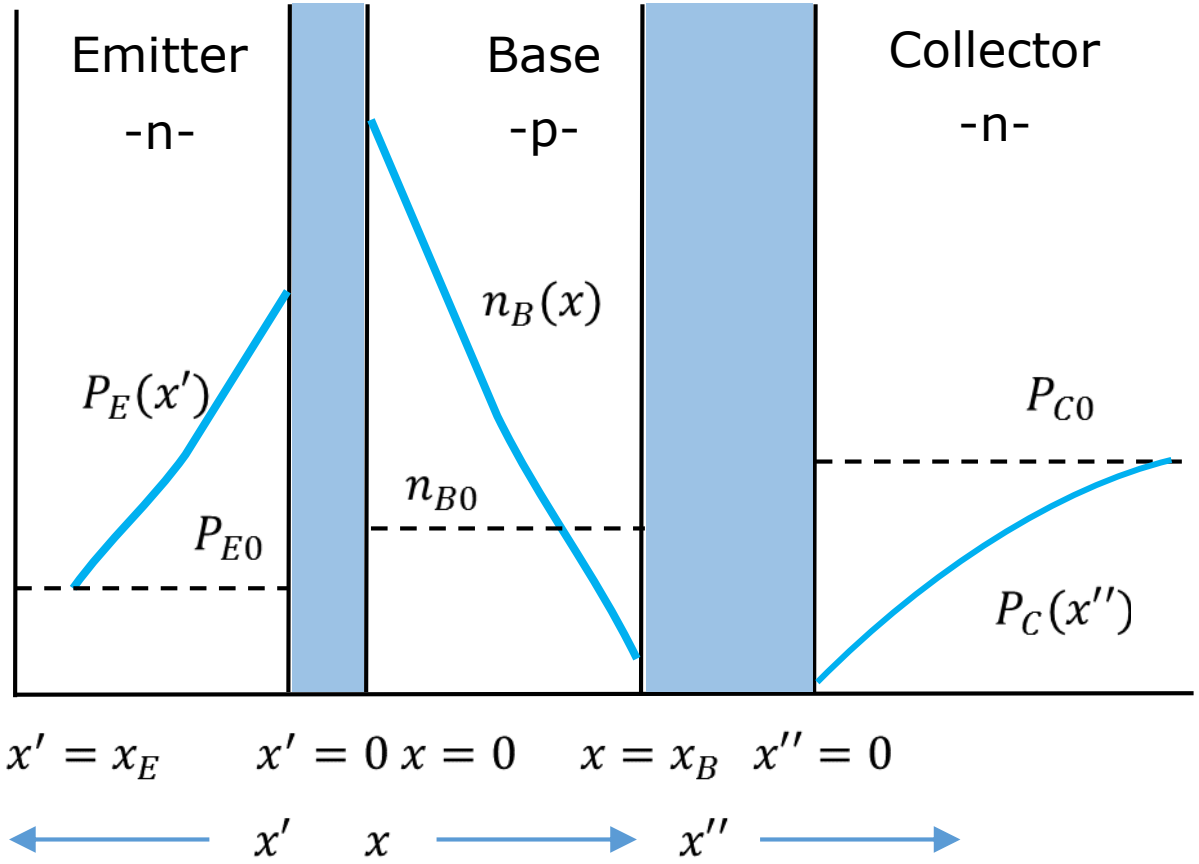


Figure 7.24

Problem 2 (Cont'd.)

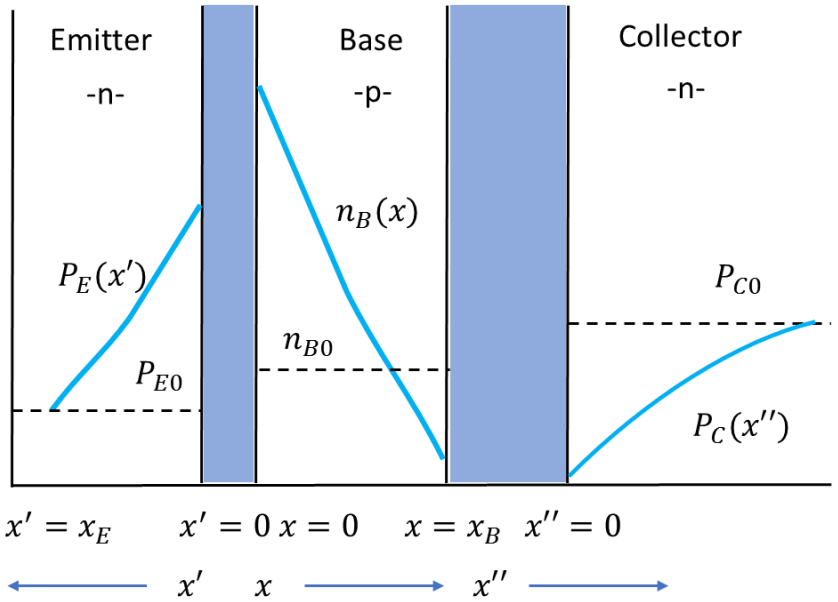
Solution (Cont'd.):

(ii)

$$P_{E0} = \frac{n_i^2}{N_E} = \frac{(1.5 \times 10^{10})^2}{8 \times 10^{17}} = 2.8125 \times 10^2 cm^{-3}$$

$$n_{B0} = \frac{n_i^2}{N_B} = \frac{(1.5 \times 10^{10})^2}{2 \times 10^{17}} = 1.125 \times 10^4 cm^{-3}$$

$$n_B(0) = n_{B0} \exp\left[\frac{V_{BE}}{V_t}\right] = (1.125 \times 10^4) \exp\left(\frac{0.640}{0.0259}\right) = 6.064 \times 10^{14} cm^{-3}$$



Since collector-base is reverse-biased, the minority carrier concentration is $<<n_{B0}\sim 0$

(iii) Emitter doping concentration higher than base and make base narrower to improve the base transport.

$$\alpha_0 \equiv \frac{I_{Cn}}{I_E} = \left[\frac{I_{En}}{I_{En}+I_{Ep}}\right]\left[\frac{I_{Cn}}{I_{En}}\right]$$

(Equation 7.1) for npn BJT

Emitter efficiency γ

Base transport factor a_T,

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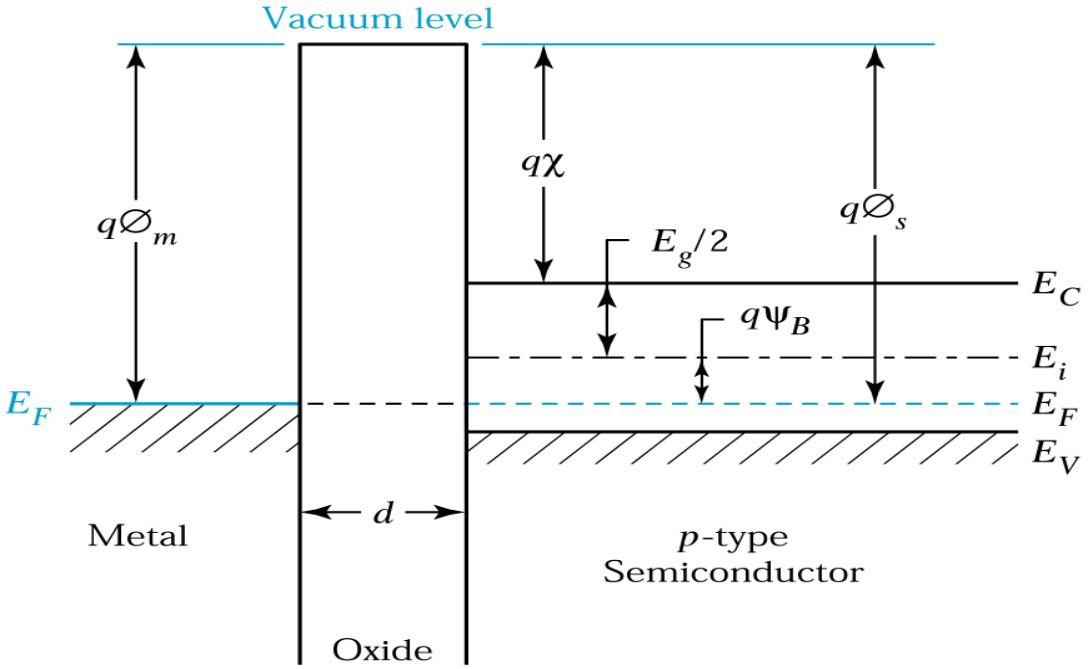
Week 3 - MOS Devices

Energy Band Diagram of an Ideal MOS Diode

The band diagram with p-type Si at V=0



$$q\phi_m = q\phi_s$$

$$q\phi_s = qx + \frac{E_g}{2} + q\psi_B$$

Figure 7.25

$q\varphi_m$: Metal work function (energy difference between Fermi level and vacuum level)

$q\varphi_s$: Semiconductor work function

$q\chi$: Electron affinity (energy difference between E_C and vacuum level)

$q\psi_B$: Energy difference between Fermi level E_F and E_i

An Ideal MOS Diode Under Bias

When an ideal MOS diode is biased, then **three cases** exist at the semiconductor surface, as shown below for p-Si.

Figure 7.26

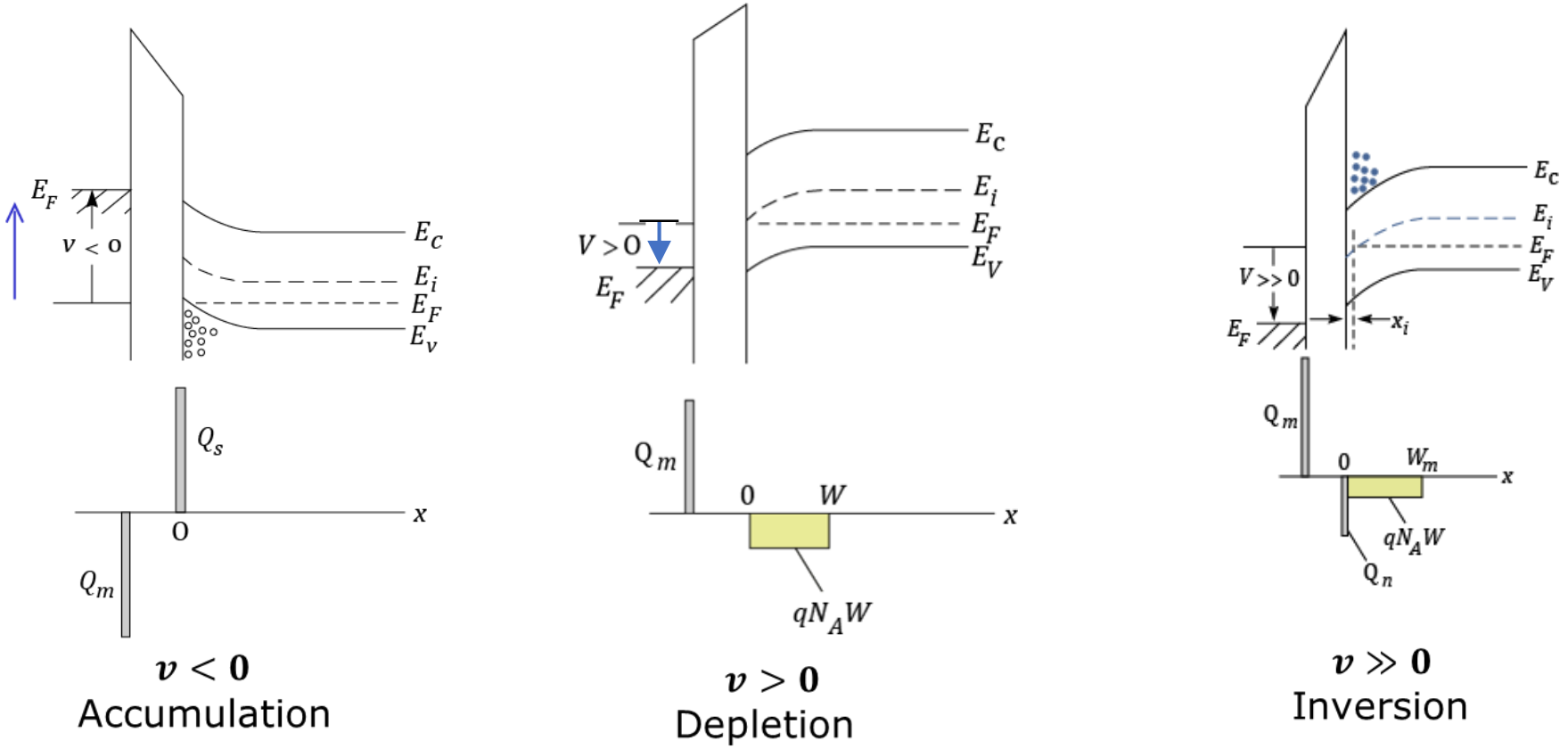


Figure 7.27

Surface Potential

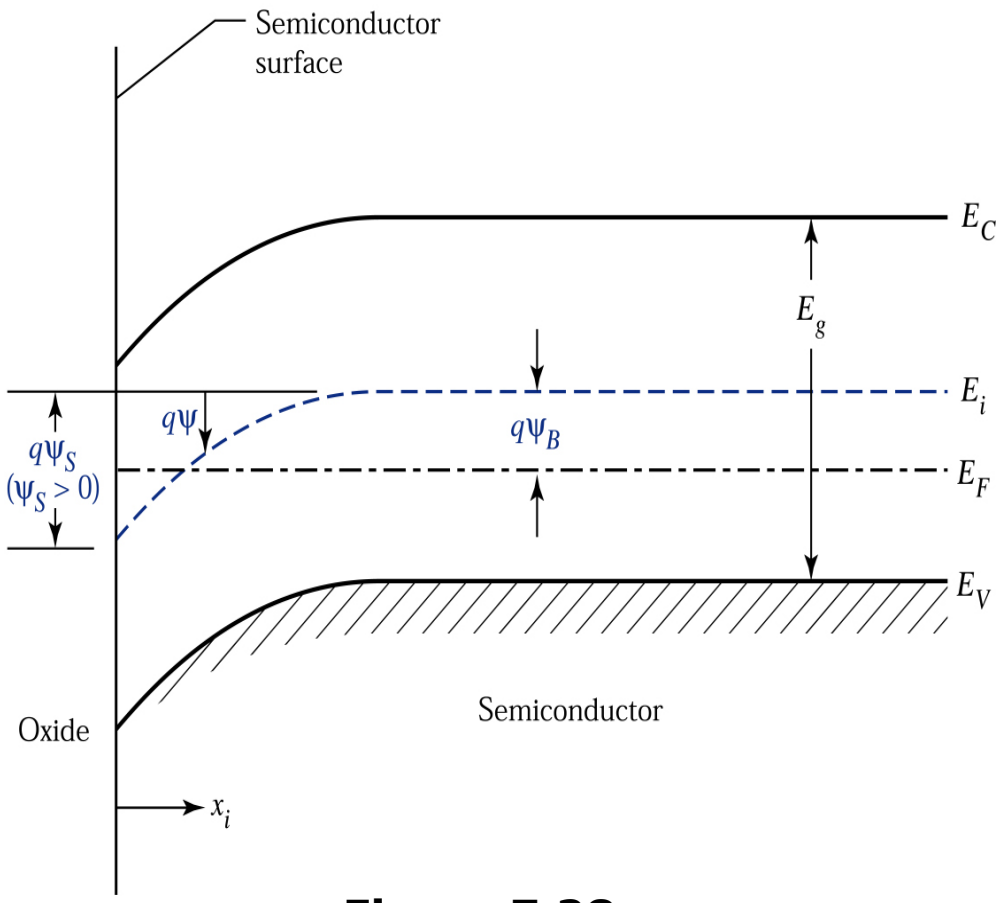


Figure 7.28

Surface potential ψ :

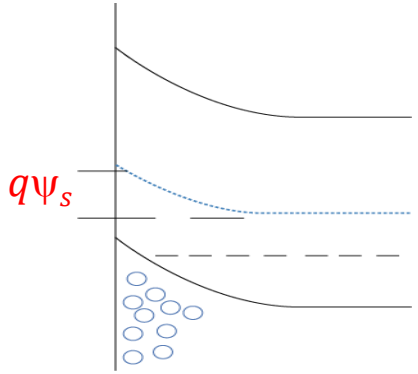
- y is zero in the bulk and y_s at the semiconductor surface.
- ψ_B: Fermi potential $q\psi_B = E_i - E_F$

$$\psi = \psi_s \left(1 - \frac{x}{W}\right)^2 \qquad \textit{(Equation 7.16)}$$

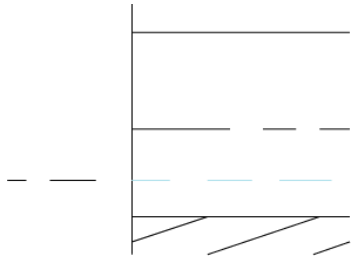
$$\psi_s = \frac{qN_A W^2}{2\varepsilon_s} \qquad \textit{(Equation 7.17)}$$

Summary

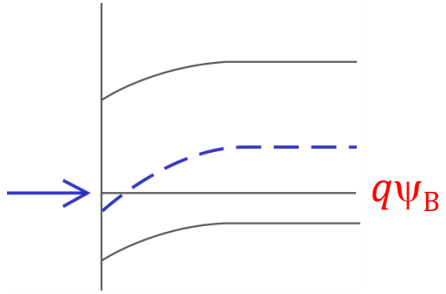
$\psi_s < 0$ **Accumulation** of holes (bands bend upward)



$\psi_s = 0$ **Flat-band** condition

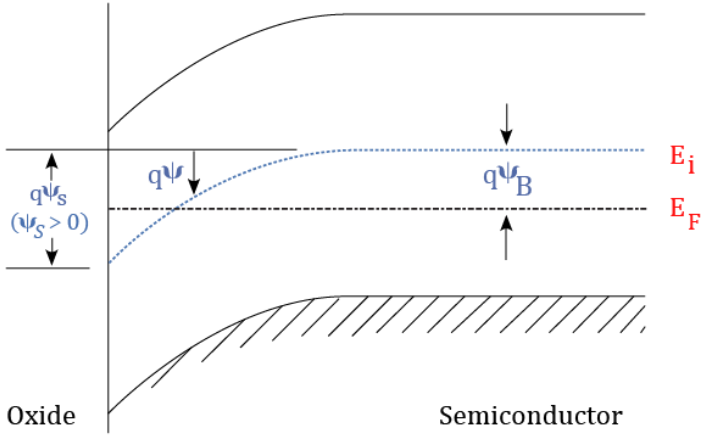


$\psi_B > \psi_s > 0$ **Depletion** of holes (bands bend downward)



$\psi_s = \psi_B$ Midgap with $n_s = n_i$ (intrinsic concentration)

$\psi_s > \psi_B$ **Inversion** (bands bend downward)



$\psi_s = \mathbf{2\psi_B}$ (onset of Strong inversion)

$$Q_s = Q_n - qN_A W_m$$

Surface Depletion Region

- At onset of strong inversion, $\psi_s = 2\psi_B$
- Surface electron concentration

$$n_p = n_i \exp\left(\frac{E_F - E_i}{kT}\right) = n_i \exp\left(\frac{q\psi_B}{kT}\right) = N_A \qquad \text{(Equation 7.17)}$$

$$\psi_s(inv) = 2\psi_B = \frac{2kT}{q}\ln\left(\frac{N_A}{n_i}\right) \qquad \text{(Equation 7.18)}$$

- Maximum width of surface depletion layer, W_m

$$W_m = \sqrt{\frac{2\varepsilon_s(2\psi_B)}{qN_A}} = \sqrt{\frac{4\varepsilon_s kT\ln\left(\frac{N_A}{n_i}\right)}{q^2 N_A}} \qquad \text{(Equation 7.19)}$$

$$Q_s = -qN_A W_m \cong -\sqrt{2q\varepsilon_s N_A(2\psi_B)} \qquad \text{(Equation 7.20)}$$

Ideal MOS Capacitance

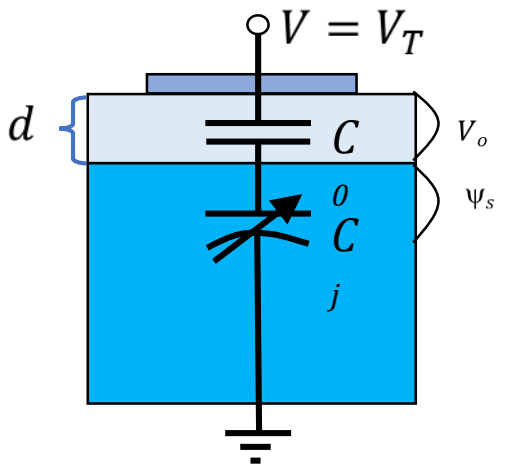


Figure 7.29

$$C = \frac{C_0 C_j}{(C_0 + C_j)} \; F.cm^{-2} \quad \textit{(Equation 7.21)}$$

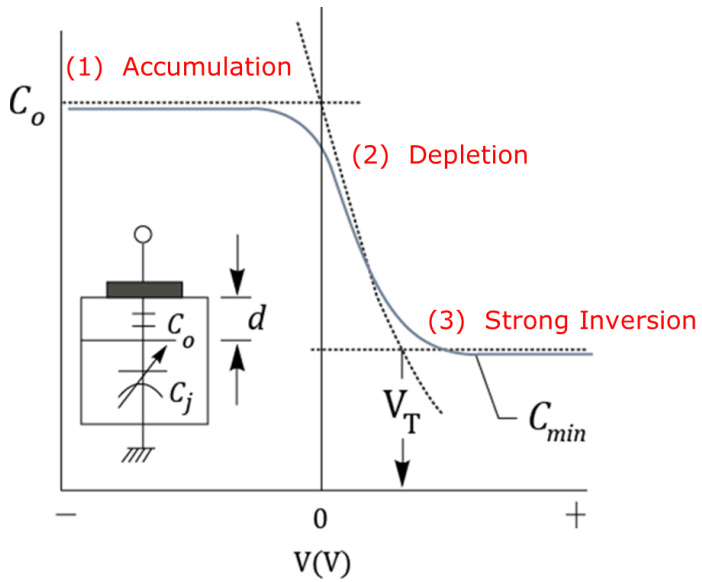


Figure 7.30. High-Frequency C-V

(1) V<0 Accumulation $C(max) \approx C_0 = \frac{\varepsilon_{ox}}{d} = constant$ *(Equation 7.22)*

(2) V>0 (from V=0 to V=V_T), Depletion

$$\frac{C}{C_0} = \frac{1}{\sqrt{1 + \frac{2\varepsilon^2{}_{ox} V}{q N_A \varepsilon_s d^2}}} \quad \textit{(Equation 7.23)}$$

(3) V>>0 (V>V_T), Strong Inversion $C(min) = \frac{C_0 C_j}{C_0 + C_j} = \frac{\varepsilon_{ox}}{d + (\varepsilon_{ox}/\varepsilon_s) W_m}$ *(Equation 7.24)*

Threshold Voltage V_T

$$V_T = \frac{q N_A W_m}{C_o} + 2\psi_B = \frac{\sqrt{2\varepsilon_s q N_A (2\psi_B)}}{C_o} + 2\psi_B$$

(Equation 7.25)

Non-Ideal MOS Diode: Work Function Difference

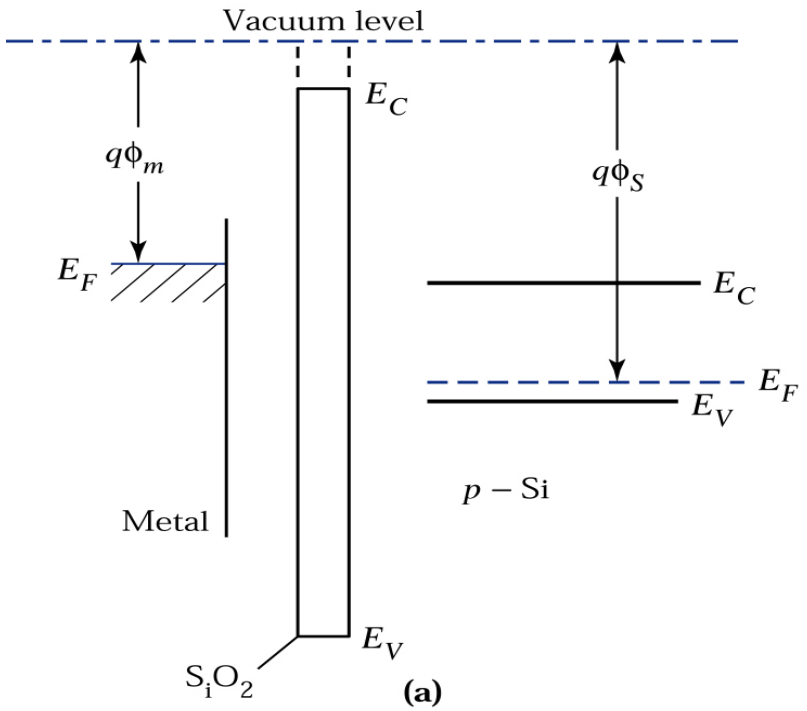


Figure 7.31 (a)
Energy band diagrams - Before contact

$q\varphi_m < q\varphi_s$

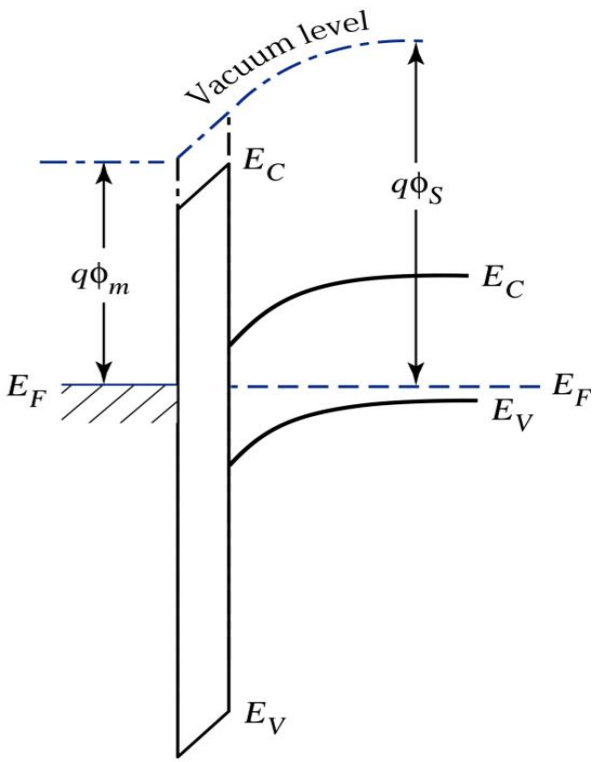


Figure 7.31 (b)
Energy band diagrams - After contact

$$V_{FB} = \phi_{ms} = \phi_m - \phi_s \qquad V_T = \frac{qN_A W_m}{C_o} + 2\psi_B + \phi_{ms}$$ *(Equation 7.26)*

Interface Traps and Oxide Charges

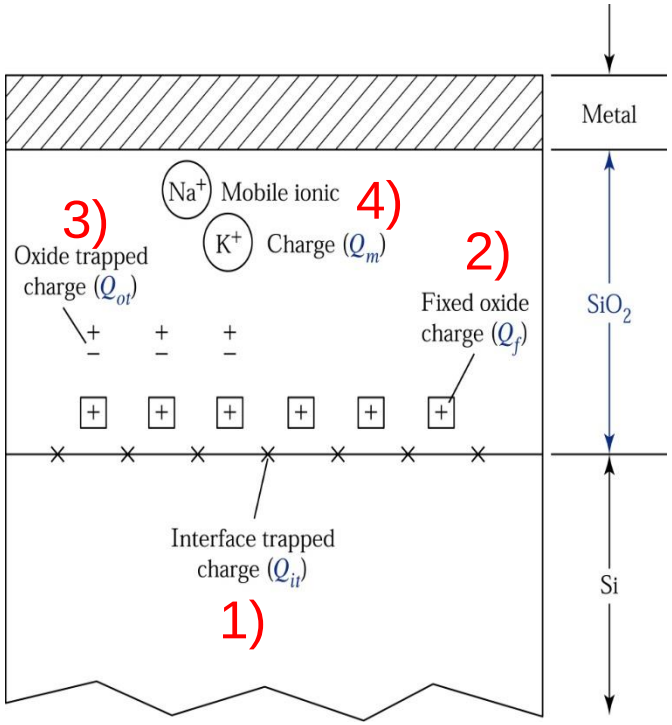


Figure 7.32

$$V_{FB} = \phi_{ms} - \frac{Q_f + Q_m + Q_{ot}}{C_o} \qquad \textit{(Equation 7.27)}$$

$$V_T = \frac{N_A W_m}{C_o} + 2\psi_B + \phi_{ms} - \frac{Q_f + Q_m + Q_{ot}}{C_o} \qquad \textit{(Equation 7.28)}$$

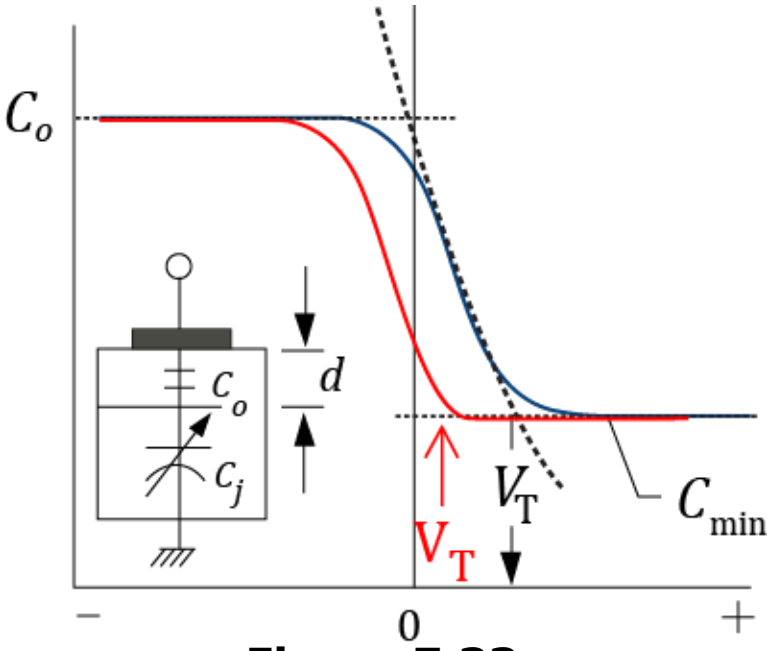


Figure 7.33

1) Interface trapped charges Q_{it}
2) Fixed oxide charges Q_f
3) Oxide trapped charges Qot
4) Mobile ionic charges Q_m

NMOSFET Operation

(1) When $V_G>0$ but $<V_T$ → Cut-off

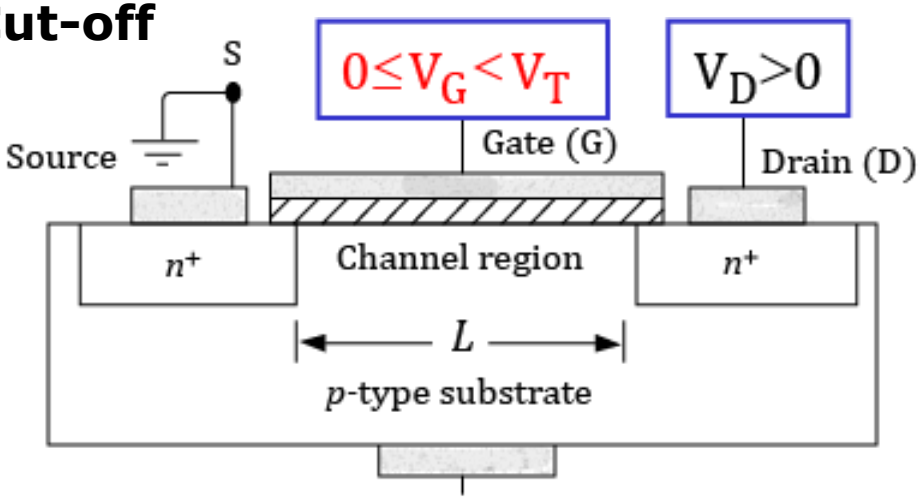


Figure 7.34

(2) When $V_G \ge V_T$ → Device on (Inversion)

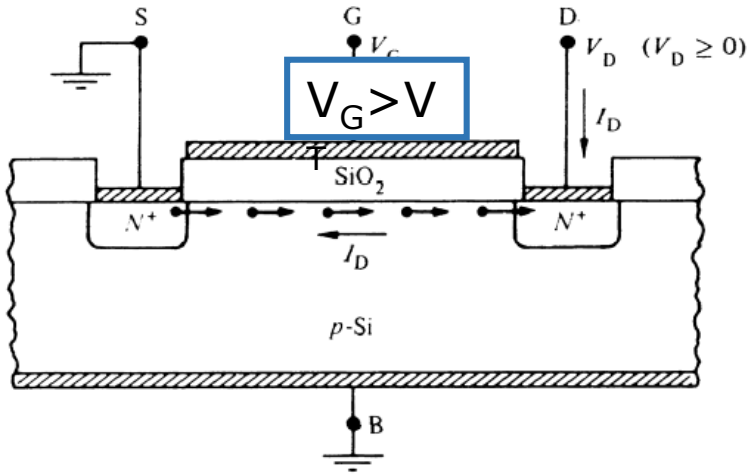


Figure 7.35

MOSFET Operation

(1) When $V_D < V_{GS} - V_T$ ➔ Linear Region

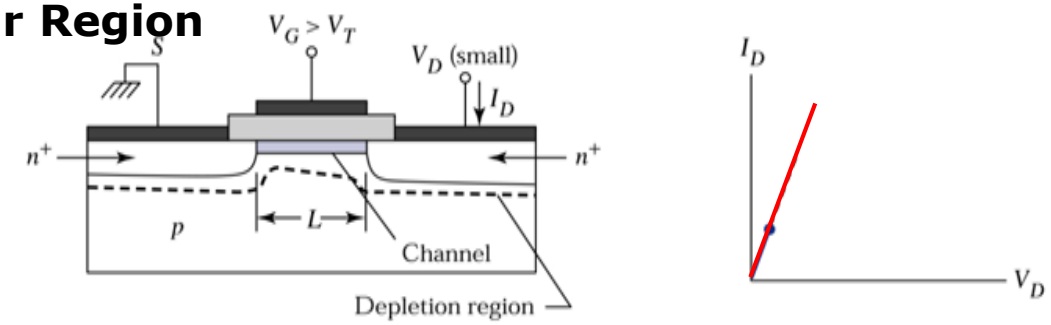


Figure 7.36

(2) When $V_D = V_{dsat} = = V_{GS} - V_T$ ➔ Pinch-off or on set of saturation Region

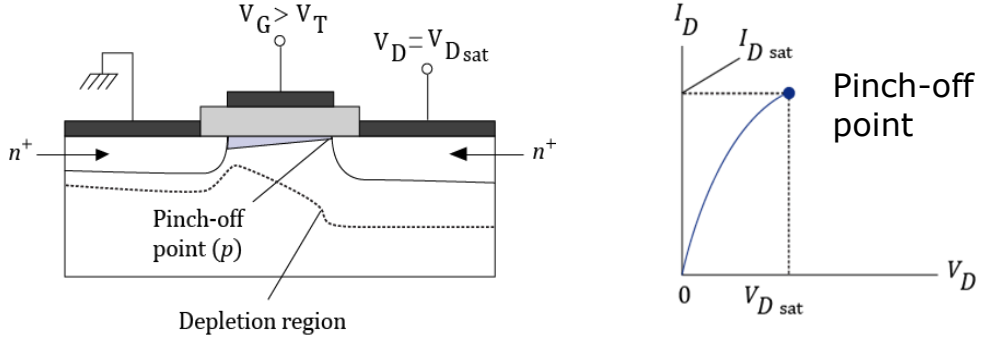


Figure 7.37

(3) When $V_D > V_{Dsat}$, ➔ Saturation Region

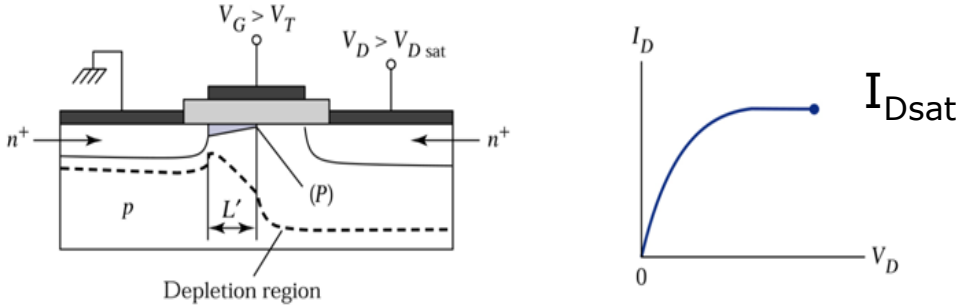


Figure 7.38

I-V Behavior of a NMOSFET

1) Cut-off region:

$$I_D = 0 \text{ for } V_{GS} \leq V_T$$

2) Linear (Triode) region:

$$I_D = K_n[(V_{GS} - V_T)]V_{DS} - \frac{V_{DS}^2}{2}] \qquad \textit{(Equation 7.29)}$$

for $V_{DS} \leq V_{GS} - V_T$

3) Saturation region:

$$I_D = \frac{K_n}{2}(V_{GS} - V_T)^2 \qquad \textit{(Equation 7.30)}$$

for $V_{DS} \geq V_{GS} - V_T$

$$K_n = \mu_n Cox\,(Z/L) \qquad \textit{(Equation 7.31)}$$

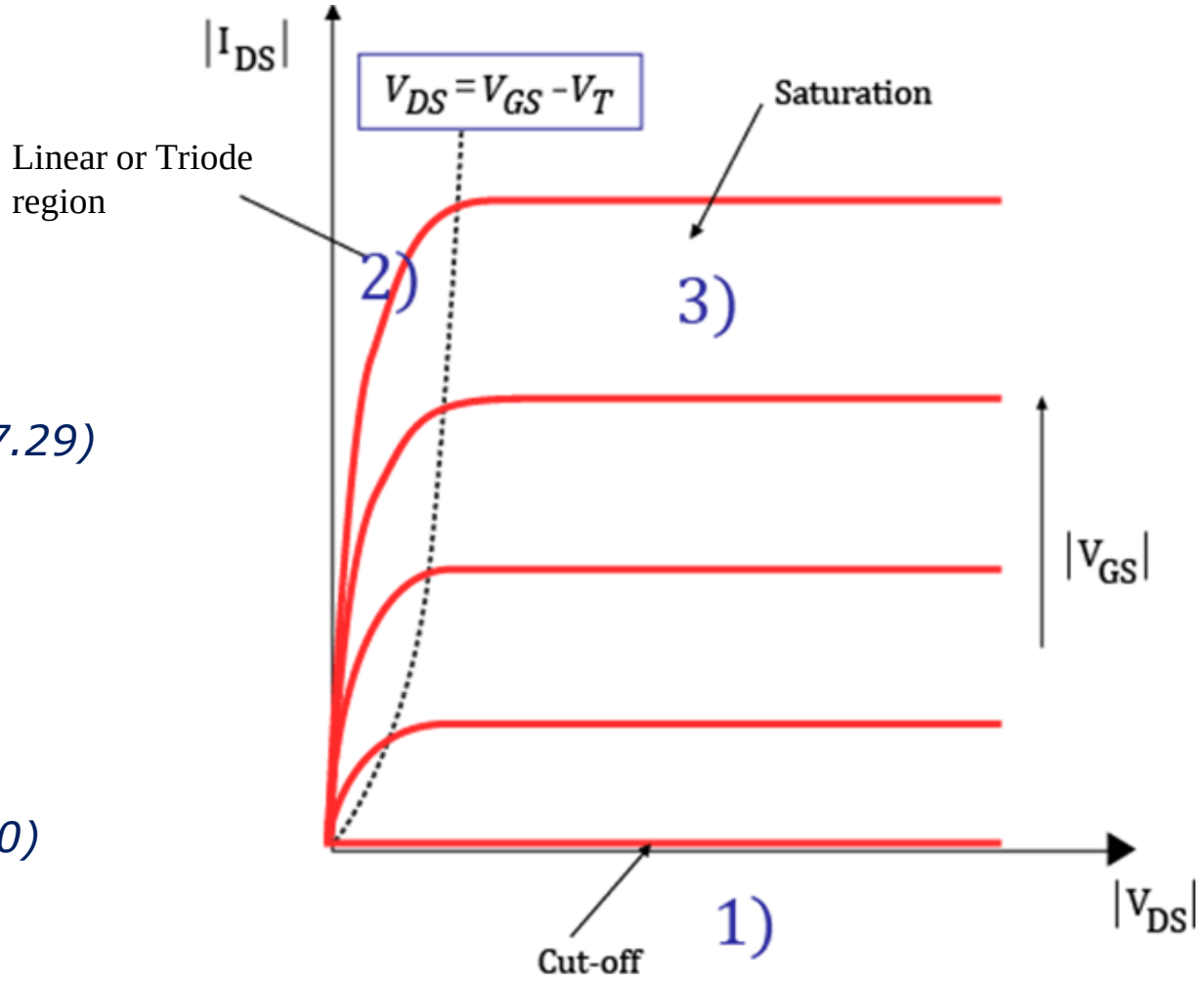


Figure 7.39

Cut-off Frequency of MOSFETs

- Similar to BJT, the cutoff frequency of a MOSFET may also be expressed as

$$f_T = \frac{1}{2\pi\tau_T} \qquad \textit{(Equation 7.32)}$$

- Transit time can be obtained by

$$\tau_T = \frac{L}{v_s} \qquad \textit{(Equation 7.33)}$$

where v_s is the electron velocity in the channel.

Problem 3

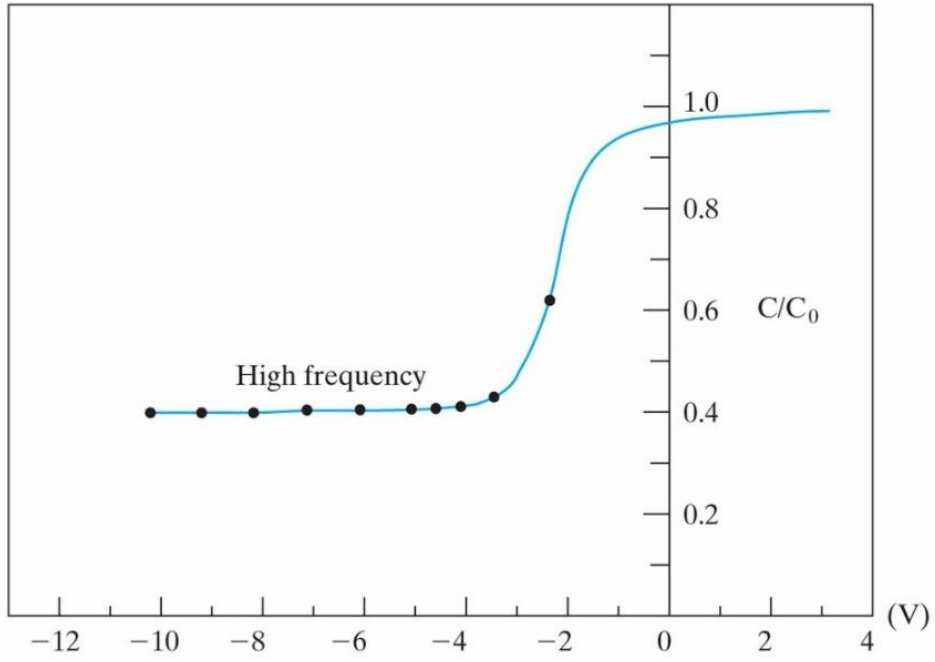
Question:

The silicon dioxide thickness (t_{ox}) and the doping concentration (N_a or N_d) of the silicon substrate can be determined using the high-frequency C-V data shown in the Figure below for an MOS structure.

i. What is the doping type of the semiconductor?

ii. If the maximum capacitance of the structure C_0 (which is equal to C_{ox} x Area) is 82 pF and the gate area is 4.75×10^{-3} cm^2, what is the value of t_{ox}?

iii. Calculate the depletion capacitance at strong inversion.



Problem 3 (Cont'd.)

Solution:

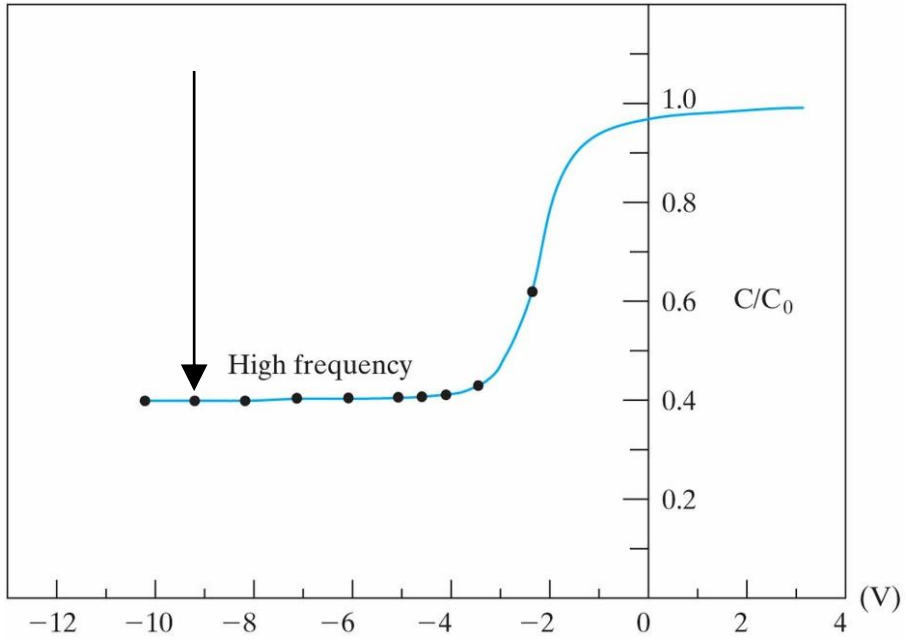
i. N-type substrate

ii. $C_0 = (\varepsilon_{ox}/t_{ox})A$

$t_{ox} = (3.9)(8.85\text{x}10^{-14})(4.75\text{x}10^{-3})/(82\text{x}10^{-12})$ = **<u>200 nm</u>**

iii. For high-frequency C-V curve, $C_{min} = (Co^{-1} + C_{dep}^{-1})^{-1}$

Plugging in $C_{min}=0.4C_o$ ➔ $C_{dep} = 0.67C_o$ = **<u>54.9 pF</u>**



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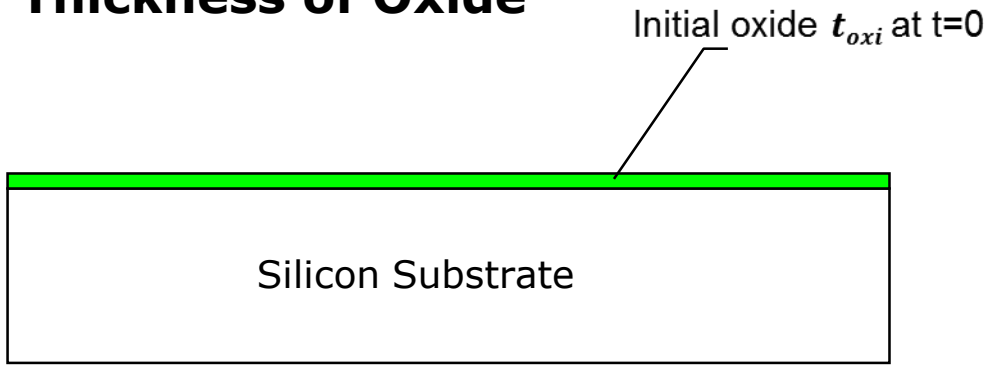
Week 4 - Thermal Oxidation

Thermal Oxidation

- **Applications:**
  - Mask for implantation and diffusion,
  - Isolation,
  - Gate oxide of MOS structures for insulation, and
  - Surface passivation.

- There are two oxidation methods:
  - Dry oxidation, and
  - Wet oxidation.

- **Thickness of Oxide**



$$t = \frac{t_{ox}^2}{B} + \frac{t_{ox}}{B/A} - \tau$$

or $$t_{ox}^2 + At_{ox} = B(t+\tau)$$ *(Equation 7.34)*

where $A = \frac{2D}{k_s}$, $B = \frac{2DN_0}{M}$ and $\tau = \frac{t_{oxi}^2}{B} + \frac{t_{oxi}}{B/A}$

t is time, t_{oxi} is the initial oxide thickness on the wafer before oxidation and τ is the time required to grow the initial oxide.

Thickness of Oxide

$$t_{ox} = \frac{-A + \sqrt{A^2 + 4B(t+\tau)}}{2}$$ *(Equation 7.35)*

- For **short time** with $t + \tau << A^2/4B$:

$$t_{ox} = \frac{B}{A}(t+\tau)$$ *(Equation 7.36)*

- For **long time** with $t + \tau >> A^2/4B, \quad t > \tau$:

$$t_{ox} = \sqrt{Bt}$$ *(Equation 7.37)*

Note:

- B/A is called **linear rate** coefficient. (Growth rate is limited by the reaction at the silicon interface; it depends on Si-Si bond strength and not by diffusivity.)
- B is called **parabolic rate** coefficient. (Oxidation rate is diffusion limited.)

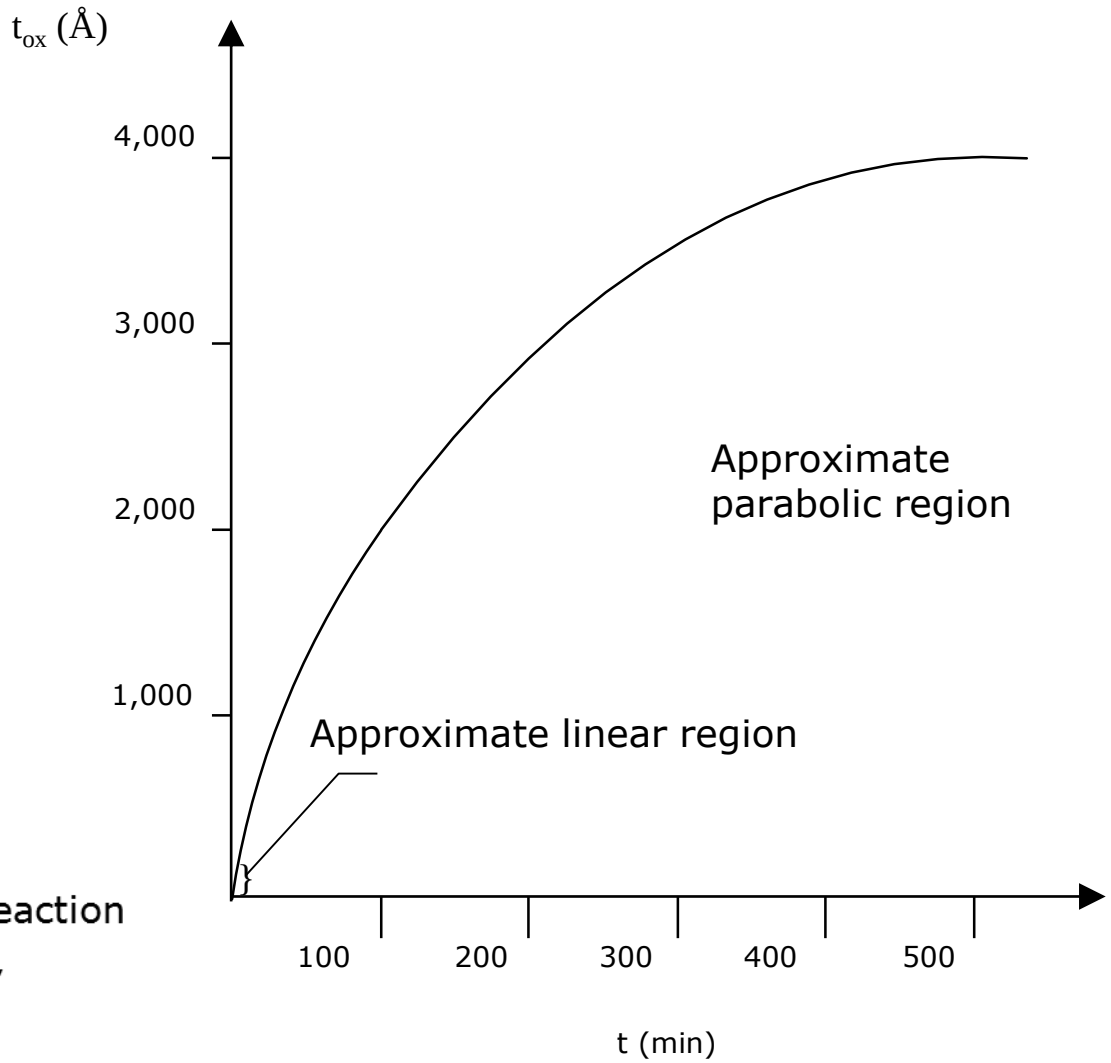


Figure 7.40

Thickness of Oxide (Cont'd.)

Factors affecting Oxidation Rate

- Growth techniques: Wet versus dry
- Growth temperature
- Pressure
- Crystal orientation: <100> versus <111>
- Impurity doping

Oxide Thickness Measurement Techniques

- Color Chart
- Ellipsometry
- **TEM** (Transmission Electron Microscopy)

Problem 4

Question:

i. Name three factors which could affect the oxidation rate.

ii. A p-type (100) Si wafer has an initial 0.50μm silicon oxide grown on top of it. It is then put back in the furnace in dry oxygen at 1200°C for 12 min. Given that this oxidation A=0.04μm and B=0.045μm^2 condition, determine the total oxide thickness?

Problem 4 (Cont'd.)

Solution:

i. Any of the three following factors:

1. Growth techniques: Wet versus dry
2. Growth temperature
3. Pressure
4. Crystal orientation: (100) versus (111)
5. Impurity doping

Problem 4 (Cont'd.)

Solution (Cont'd.):

ii. Since there is an initial oxide thickness (of 0.5 micron) before the dry oxidation, $t_{ox}^2 + At_{ox} = b(t+\tau)$ *(Equation 7.34)*

Note that originally, there is a 0.5μm thick oxide, we have to find τ in dry oxidation for the 0.5μm thick oxide in order to calculate the thickness of the next oxide grown by dry oxidation.

$0.5^2 + A \times 0.5 = B\tau$ where $A = 0.04\mu\text{m}, B = 0.045\mu\text{m}^2/hr$.

Solving the *equation*, we have $\tau = 6hr$.

Since the dry oxidation is done for 12 min (or 0.2hr), the total oxide thickness after the dry oxidation can be obtained.

$t_{ox}^2 + 0.04 \times t_{ox} = 0.045 \times 6.2$ Hence, $t_{ox} = 0.5086\mu\text{m}$

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Week 5 - Thermal Diffusion

Thermal Diffusion

- Diffusion is the key process for introducing impurities in the selected regions of a semiconductor.

When to use diffusion process:

- To use it when damage from Ion Implantation is unacceptable, electrical junctions need to be very deep, or a cheap, easy solution is needed.
- Not to use for ultra-shallow junctions, or total impurity "dose" is critical.

Two principal mechanisms for dopants to diffuse in the crystal:

(1) Interstitial diffusion:

- Impurity atoms diffuse between interstitial spaces (do not replace atoms in the crystal lattice).
- They do not directly contribute to doping.

(2) Substitutional diffusion:

- Impurity atoms jump from one lattice site to another lattice site.
- Since the number of lattice vacancies are limited, it is a slow process.
- Substitutional diffusion is responsible for doping effects.

Impurity Concentration Profile

There are two types of boundary conditions important in modeling the impurity diffusion in Si - **Constant-source diffusion** and **Limited-source diffusion**.

(1) <u>Constant-source diffusion:</u>

- The impurity concentration at the surface of the solid remains constant, N_s (unlimited supply of excess impurity atoms is available at surface).
- The diffusion profile is given by:

$$N(z) = N_s \operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}}\right) \quad \textit{(Equation 7.38)}$$

erfc: Complementary error function $\sqrt{Dt}$: Characteristic diffusion length.

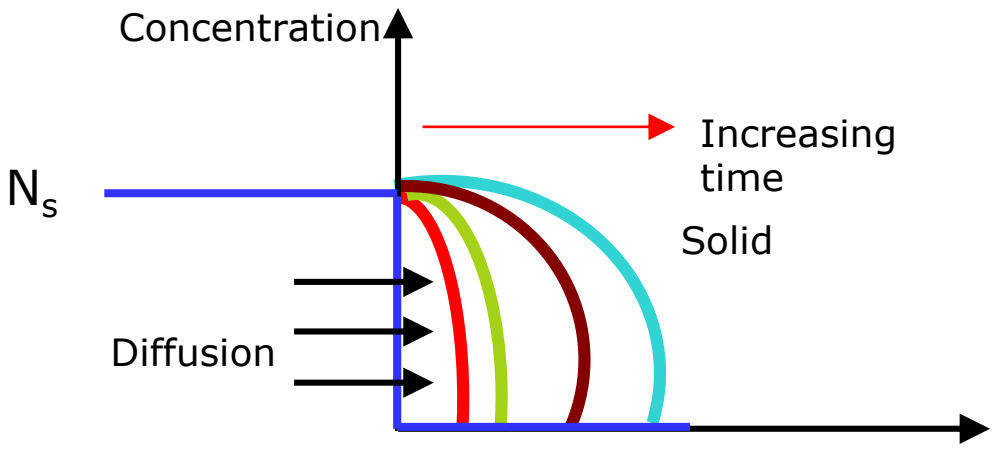

Figure 7.41

- Total number of the impurity atoms entered into the Si per unit area is called dose:

$$Q(t) = \int_0^\infty N_s \operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}}\right) dz \rightarrow Q(t) = \frac{2N_s}{\sqrt{\pi}}\sqrt{Dt} \quad \textit{(Equation 7.39)} \quad \text{where} \quad D = D_0 \exp\left(-\frac{E_a}{kT}\right)$$

(2) Limited Source Diffusion

Consider a case when a thin layer of fixed amount of dopant, (Q atoms /cm^2) is initially deposited onto the semiconductor surface, and then, diffusion is carried out. **The total amount of impurity atoms at surface is fixed.**

- The diffusion profile is given by:

$$N(z) = \frac{Q}{\sqrt{\pi D t}} exp - \left(\frac{z}{2\sqrt{Dt}}\right)^2 \qquad \textit{(Equation 7.40)}$$

Gaussian profile

- The surface concentration (at z=0) is:

$$N(0,t) = N_s = \frac{Q}{\sqrt{\pi D t}} \qquad \textit{(Equation 7.41)}$$

Figure 7.42

(2) Limited Source Diffusion (Cont'd.)

A limited source diffusion is a combination of two processes, pre-deposition and drive in.

(1) Pre-deposition, a thin layer with limited amount of dopants is deposited on surface at a short time t. The total amount gives a dose:

$$Q = 2N_s\sqrt{\frac{Dt}{\pi}}$$ *(Equation 7.42)*

(2) <u>Drive in</u>, the pre-deposited dopants on the surface (with fixed amount) are made to diffuse deeper into the solid thus making the dopants redistribute following the **Gaussian profile**. With the increase of diffusion time, the dopants go deeper and deeper but the total amount does not change.

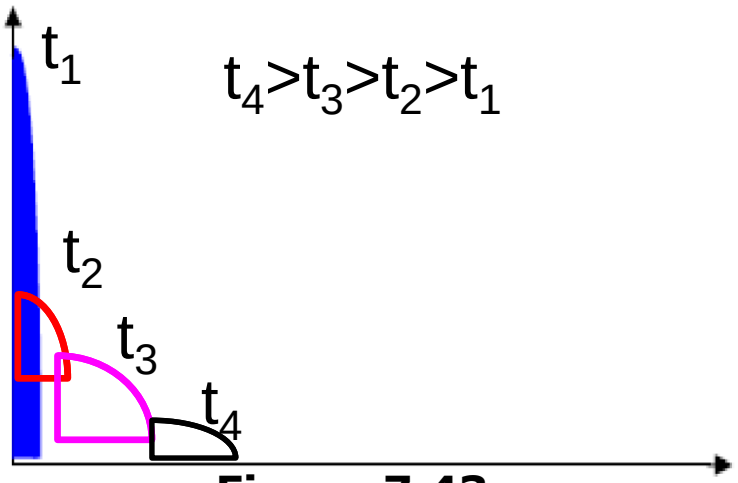

Figure 7.43

Junction Formation by Diffusion

- **p - type** dopant with **N(z, t)> N_B**

- For constant source diffusion, Junction is located at z_j such that:

$$N_s \mathrm{erfc}\left(\frac{z_j}{2\sqrt{Dt}}\right) = N_B. \qquad \textit{(Equation 7.43)}$$

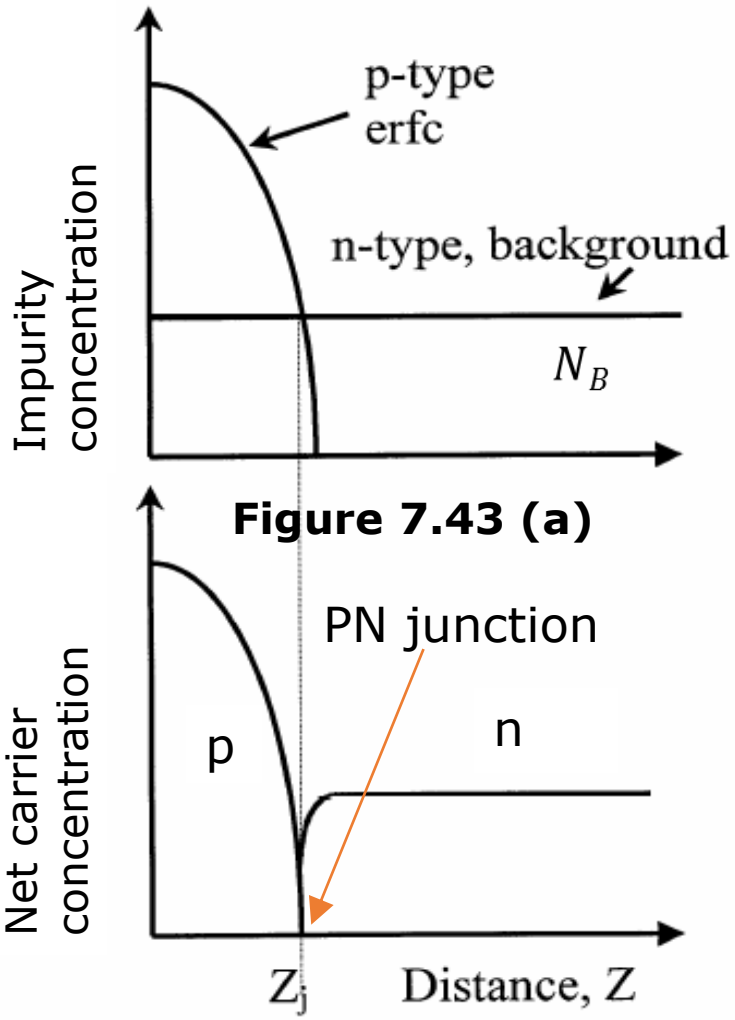

Figure 7.43 (a)

Figure 7.43 (b)

Problem 5

Question:

At 1100°C, a boron diffusion into a n-type wafer with a background concentration of 4.0 x $10^{15} cm^{-3}$ results in a Gaussian profile with a surface concentration of 5.0 x $10^{18} cm^{-3}$ and a junction depth of 4μm.

(i) Calculate the diffusion coefficient if D_o = 10.5cm^2/s and E_a = 3.69eV.

(ii) Determine the diffusion time taken to form the junction.

Problem 5 (Cont'd.)

Solution:

(i) $D = D_0 \exp\left(-\frac{E_a}{kT}\right)$

At $1100^\circ C = 1373k, D = 10.5 \exp\left\{-\frac{3.69}{kT}\right\} = 2.99 \times 10^{-13} cm^2/sec$

(ii) $N(z) = \frac{Q}{\sqrt{\pi D t}} exp - \left(\frac{z}{2\sqrt{Dt}}\right)^2$

$5 \times 10^{18} \exp\left[-\left(\frac{X_j}{2\sqrt{Dt}}\right)^2\right] = 4.0 \times 10^{15}$.

Solving for Dt with $X_j = 4 \times 10^{-4} cm$ yields $Dt = 5.61 \times 10^{-9} cm^2$, and $D = 10.5 \exp\left[-\frac{3.69}{kT}\right] = 2.99 \times 10^{-13} cm^2/sec$ yielding $t = 1.88 \times 10^4 sec$ or 5.21 hours (313 minutes).

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Week 6 - Ion Implantation

Ion Implantation

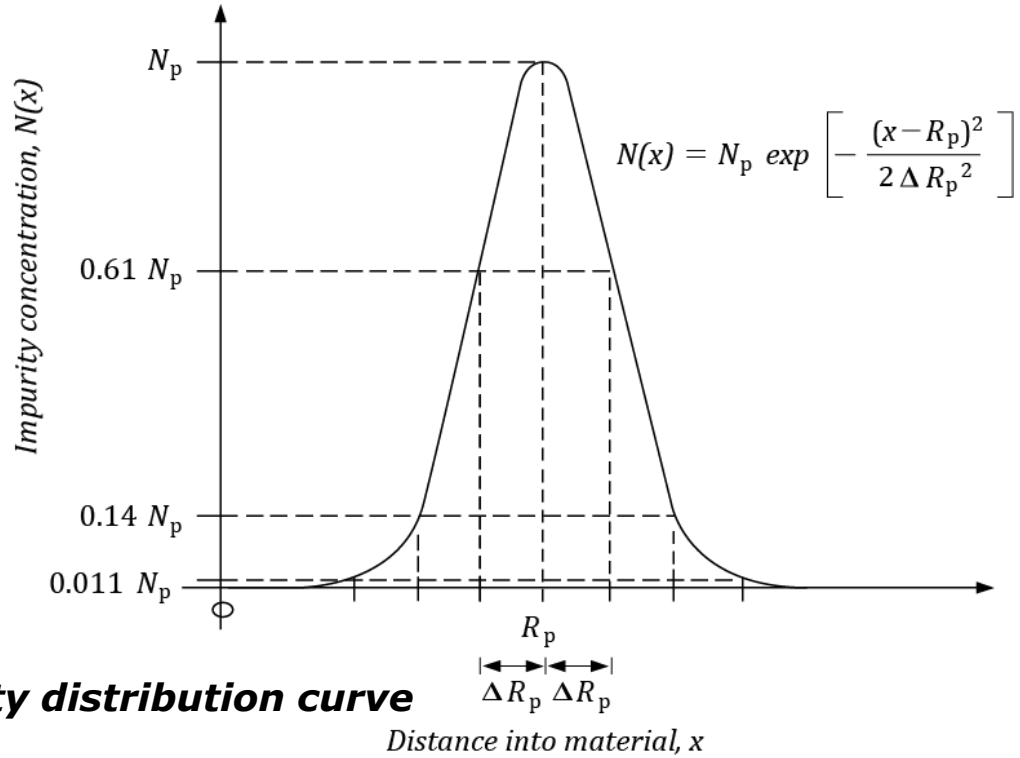
- Impurity profile is approximated to a Gaussian distribution function along the axis of incidence:

$$N_p exp\left[-\frac{(x_j - R_p)^2}{2\Delta R_p^2}\right] = N_B \quad \textit{(Equation 7.44)}$$

R_p: Projected range (average distance an ion travels)

ΔR_p: Straggle (Standard deviation of the projected range)

$N(R_p)$:N_p (maximum ion concentration)



The total ions implanted into the Si is dose = the area under the impurity distribution curve

Figure 7.44

Dose $$Q = \int_0^\infty N(x)\,dx = \sqrt{2\pi}\,N_p \Delta R_p \quad \textit{(Equation 7.45)}$$

Hence $$N(x) = \frac{Q}{\sqrt{2\pi}\,\Delta R_p} \exp\left[-\frac{(x - R_p)^2}{2\Delta R_p^2}\right] \quad \textit{(Equation 7.46)}$$

Ion Channeling

- For single crystals, there are directions in which no nuclei will be encountered and the only stopping mechanism is due to electrons. Thus, the range will be considerably increased or channelled. To avoid: e.g. tilt, surface amorphise.

Masking During Implantation

The dose deposited in the wafer beyond depth ***d*** (shaded) is:

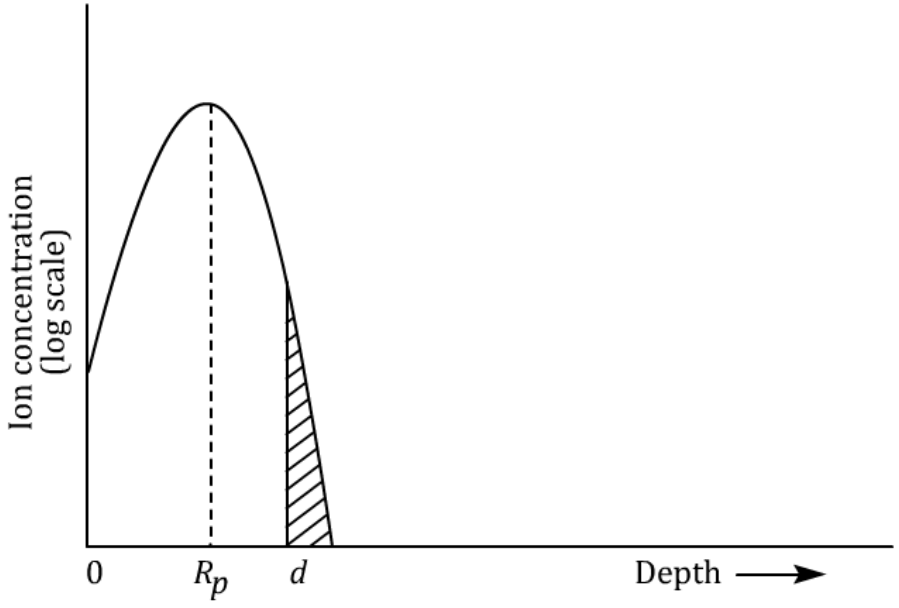
$$S(d) = \frac{S}{\sqrt{2\pi}\,\Delta R_p} \int_d^{\infty} \exp\left[-\frac{(x - R_p)^2}{2\Delta R_p^{\,2}}\right] dx$$ *Equation 7.47*

Fraction of dose implanted beyond depth *d* is:

$$\frac{S(d)}{S} = \frac{1}{2}\,\mathrm{erfc}\,\frac{(d - R_p)}{\sqrt{2}\,\Delta R_p}$$ *Equation 7.48*

To achieve masking effectiveness of 99.99%

➔ masking thickness ***d*** = (3.72ΔRp+Rp) *Equation 7.49*



Ion penetration beyond a depth *d*.

Figure 7.45

Silicon Oxide for Masking

$$N(t_{ox}) = N_p \exp\left[-\frac{(t_{ox}-R_p)^2}{2\Delta R_p^2}\right] < \frac{N_B}{10}$$ *(Equation 7.49)*

The required oxide thickness for the mask:

$$t_{ox} \geq R_p + \Delta R_p \sqrt{2\ln\left(\frac{10N_p}{N_B}\right)}$$ *(Equation 7.50)*

Junction Depth

$$N(x_j) = N_B$$

$$N_p exp\left[-\frac{(x_j-R_p)^2}{2\Delta R_p^2}\right] = N_B$$ *(Equation 7.51)*

$$x_j = R_p \pm \Delta R_p \sqrt{2\ln\left(\frac{N_p}{N_B}\right)}$$ *(Equation 7.52)*

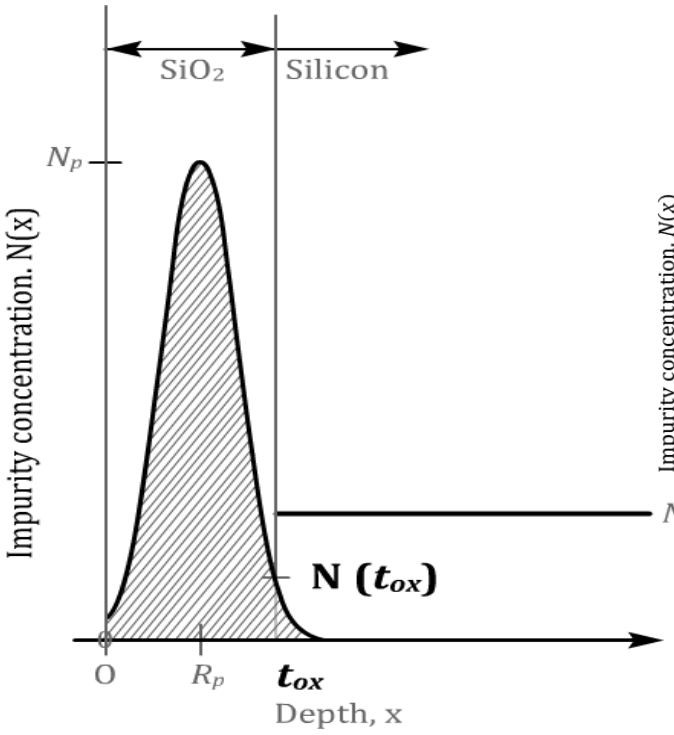


Figure 7.46

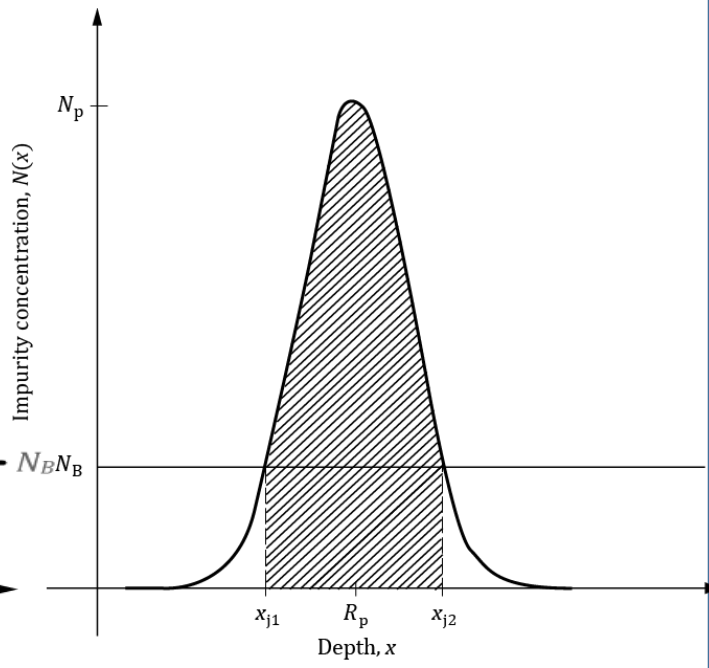


Figure 7.47

Effect of Annealing on Implantation Profile

- R_p remains the same, but ΔR_p alters to:

$$(\Delta R_p{}^2 + 2Dt)^{1/2} \qquad \textit{(Equation 7.53)}$$

- Hence

$$N(x) = \frac{Q}{\sqrt{2\pi}(\Delta R_p{}^2 + 2Dt)^{1/2}} exp\left[-\frac{(x - R_p)^2}{2(\Delta R_p^2 + Dt)}\right] \qquad \textit{(Equation 7.54)}$$

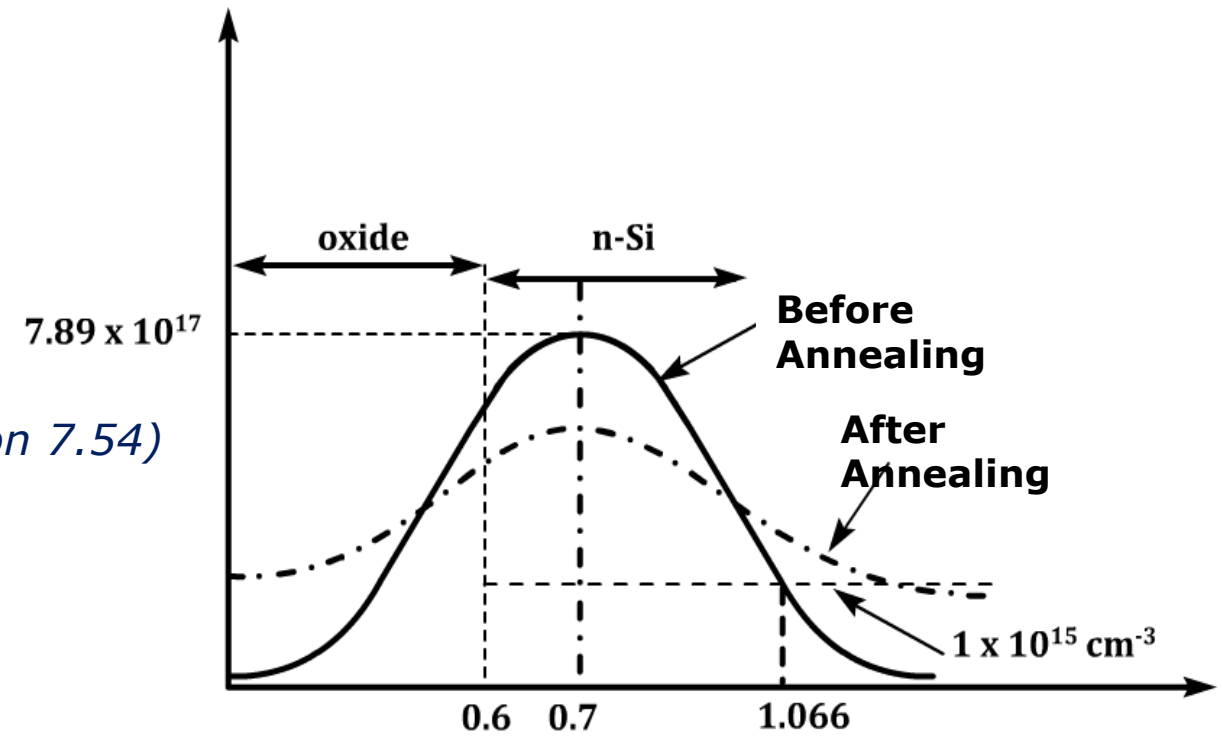


Figure 7.48

Problem 6

Question:

Boron is implanted with an energy of 60 keV through a 0.25μm layer of silicon dioxide. The implanted dose is 1×10^{14} cm^{-2}. Find the boron concentration at the silicon-silicon dioxide interface if the straggle range ΔR_p is 0.09μm and the projected range R_p is 0.19μm.

Problem 6 (Cont'd.)

Solution:

Given $R_p = 0.19\mu\text{m}$ and $\Delta R_p = 0.09\mu\text{m}$. For the Gaussian implant,

$$N(x) = N_p exp\left[-\frac{(x_j - R_p)^2}{2\Delta R_p^2}\right] \qquad \textit{(Equation 7.44)}$$

$$NP = \frac{Q}{\sqrt{2\pi}\Delta R_p} = 4.43 \times 10^{18}/c\,m^3 \qquad \textit{(Equation 7.45)}$$

$$N(0.25\mu m) = 4.43 \times 10^{18} \exp\left[-\frac{(0.25 - 0.19)^2}{2(0.09)^2}\right] = 3.5 \times 10^{18}/cm^3$$

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End of Part I