Class 04: Device Physics I

Topics:

1. Introduction
2. NFET Model and Cross Section with Parasitics
3. Band Diagrams
4. Depletion region, Voltage, Field
5. Deriving Vbi
6. Vbi as a function of doping
7. Depletion region
8. Forward, Reverse Biasing Band Diagrams
9. Thermal Equilibrium
10. Forward Bias
11. Reverse Bias
12. Junction Capacitance
13. Diode Equation

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NMOS Model and Cross Section with Parasitics (Martin p.101)

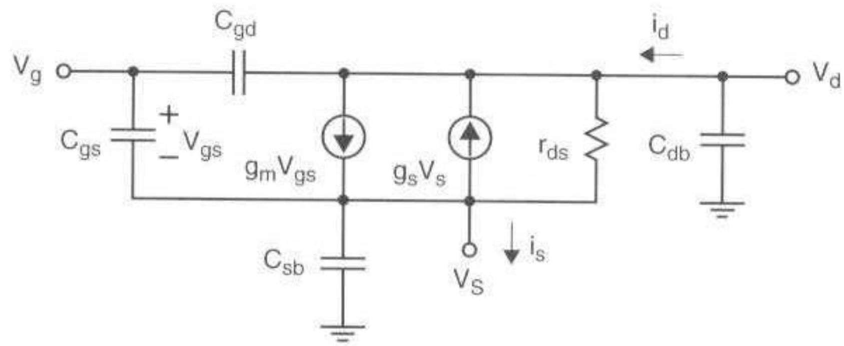

Figure 3.24 The small-signal model for an MOS transistor in the active region.

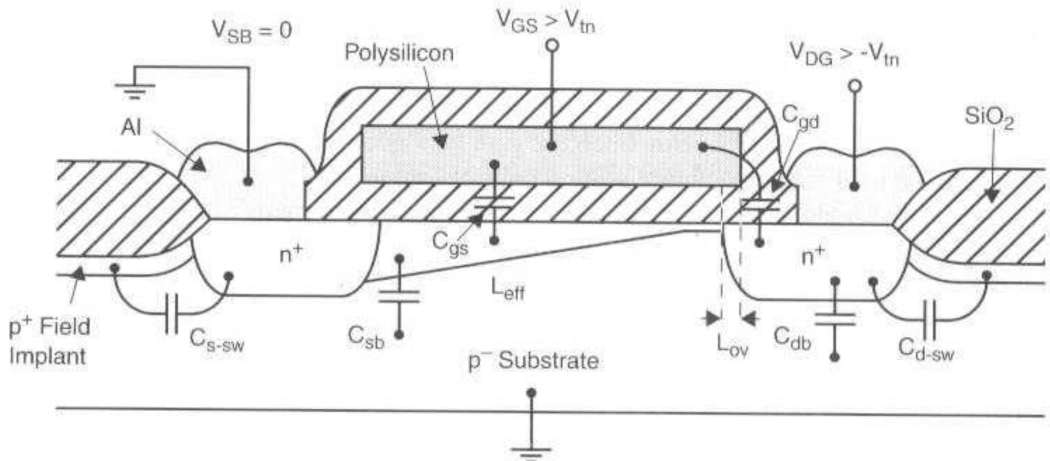

Figure 3.25 A cross section of an n-channel MOS transistor showing the small-signal capacitances.

•Goal is to understand the parasitic regions and terms shown in the model and cross section

•Question - where are the pn junctions?

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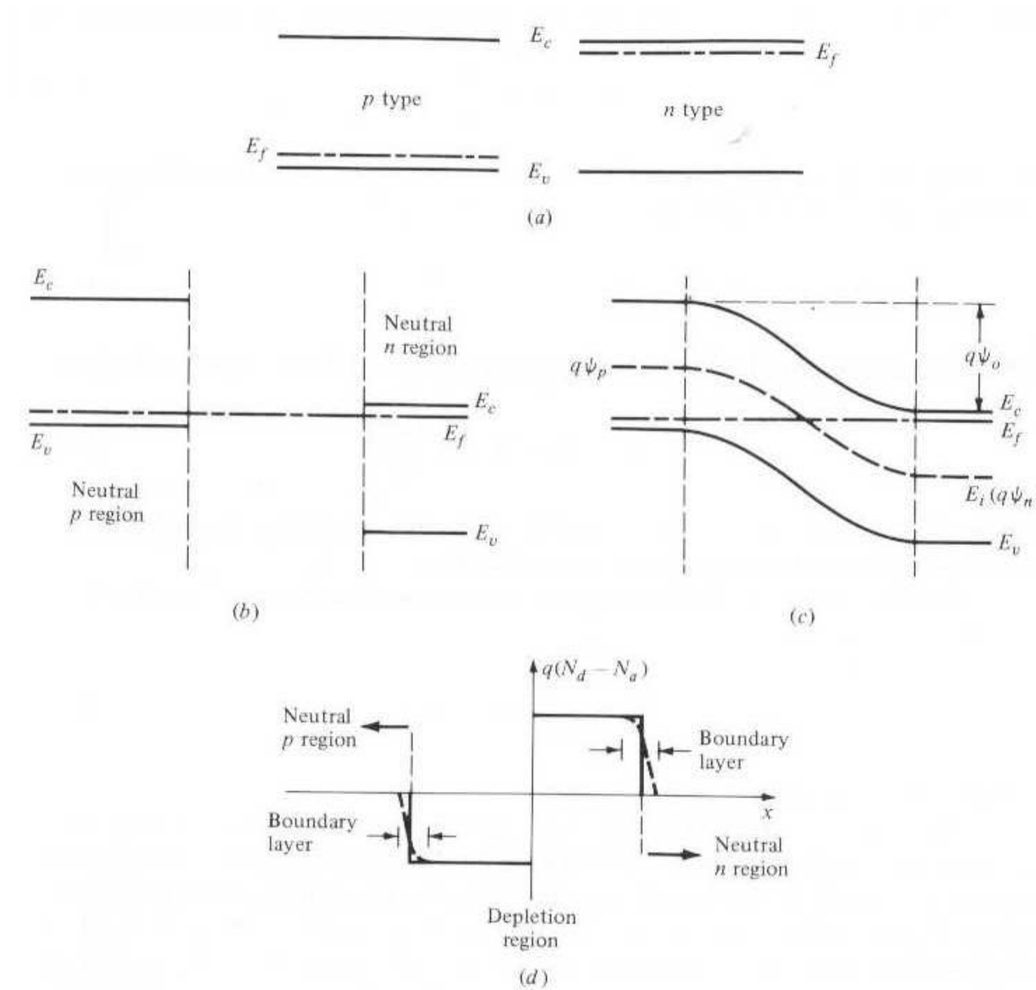
PN Junctions - Band Diagrams (Yang p.73)



Before contact

Fermi Level alignment

Space-Charge distribution

FIGURE 3-10
(a) Isolated p-type and n-type silicon before contact, (b) Fermi-level alignment, (c) the energy-band diagram after contact, and (d) the space-charge distribution of (c).

- When two dissimilar materials are joined, there is an offset in the energy levels
- The Fermi levels must align, and the band diagrams show how this is done via band bending
- The x-axis is linear dimension, and the y-axis is energy

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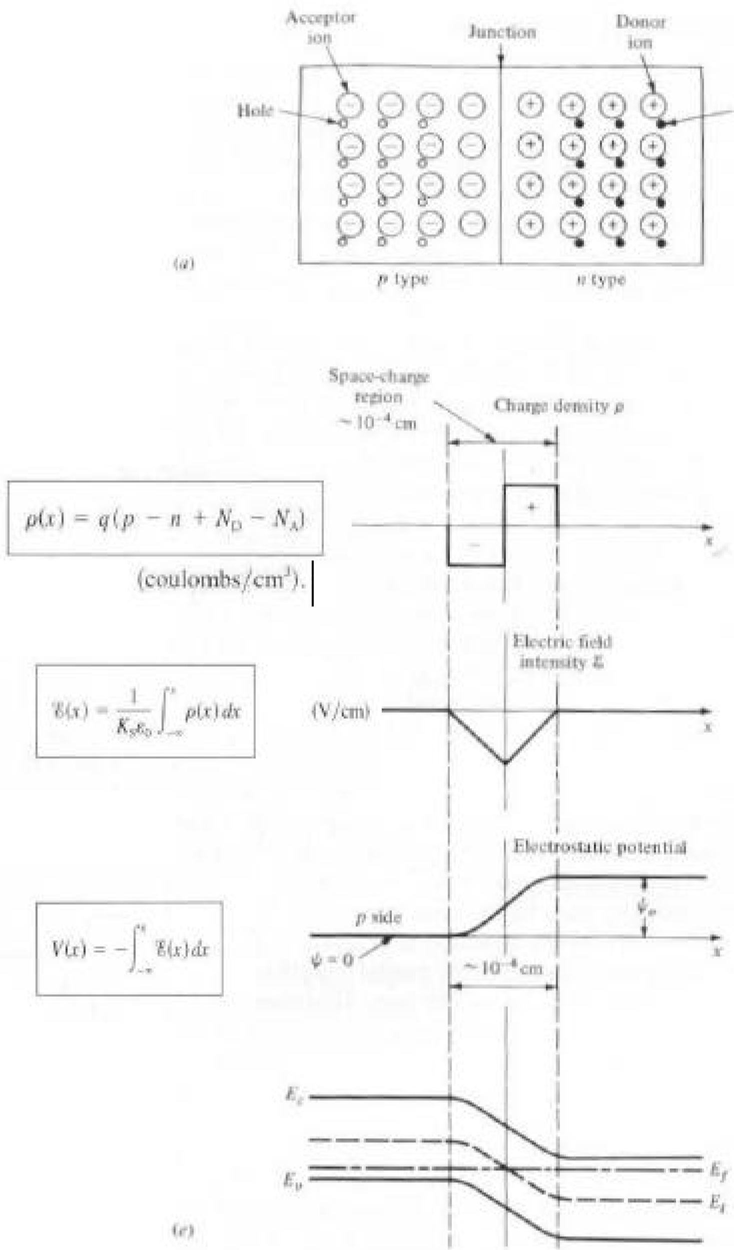
PN Junctions - Depletion, Voltage, Field (Yang p.72, Neudeck p.22,24, Mason)



- When p-type and n-type materials are joined, diffusion occurs. Excess holes in p-type region diffuse to n-type, and excess electrons in n-type diffuse to p-type region

- This diffusion is opposed by the resulting electric field of the uncovered ionic charges. The positive ion cores in the n-type region oppose the diffusion of the p-type carriers from the p-type region, and vice-versa.

- The exposed ionic cores in the p-type region (negative, Na) must be matched by the exposed ionic cores in the n-type region (positive, Nd), leaving a net charge-neutral device:

$$q\ A\ x_p N_A = q\ A\ x_n N_D$$

- If A is the same on both sides, then

$$x_p N_A = x_n N_D$$

meaning the depletion depth is greater for a more lightly doped region

- The ionic charge results in an E-field, which causes a built-in potential to form. This Vbi will oppose the diffusion and it will match the -qVbi in the band diagrams.

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PN Junctions - Deriving Vbi (Neudeck p.26,27)

•Electron current density is a combination of drift and diffusion currents, which must be zero to maintain charge neutrality

$$J_N = J_{N|\text{drift}} + J_{N|\text{diffusion}} = q\mu_n n \mathscr{E} + qD_N \frac{dn}{dx} = 0$$

•Solving for the E-Field, and using the Einstein relationship between diffusion and mobility, gives the E-field as a function of temperature

$$= \left(\frac{-qD_N}{q\mu_n n}\right)\left(\frac{dn}{dx}\right) = -\left(\frac{D_N}{\mu_n}\right)\left(\frac{1}{n}\right)\left(\frac{dn}{dx}\right) = -\left(\frac{kT}{q}\right)\left(\frac{1}{n}\right)\left(\frac{dn}{dx}\right)$$

•Integrating from one bulk region to the other

$$V_{bi} = -\int_{-\infty}^{\infty} \mathscr{E}\, dx = \frac{kT}{q}\int_{-\infty}^{\infty}\left(\frac{1}{n}\right)\left(\frac{dn}{dx}\right)dx = \frac{kT}{q}\int_{n(-\infty)}^{n(+\infty)}\frac{dn}{n}$$

•Vbi as a function of the electron carrier concentration in the n- and p-type material

$$V_{bi} = \frac{kT}{q}[\ln n_n - \ln n_p] = \frac{kT}{q}\ln\left[\frac{n_n}{n_p}\right]$$

•By using the approximations:

$$n_p = n(-\infty) = n_i^2/N_A \qquad n_n = n(+\infty) = N_D$$

•Built-in Potential across an abrupt pn junction

$$\boxed{V_{bi} = \frac{kT}{q}\ln\left[\frac{N_D N_A}{n_i^2}\right]}$$

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PN Junctions - Vbi as a function of doping (Sze p.88)

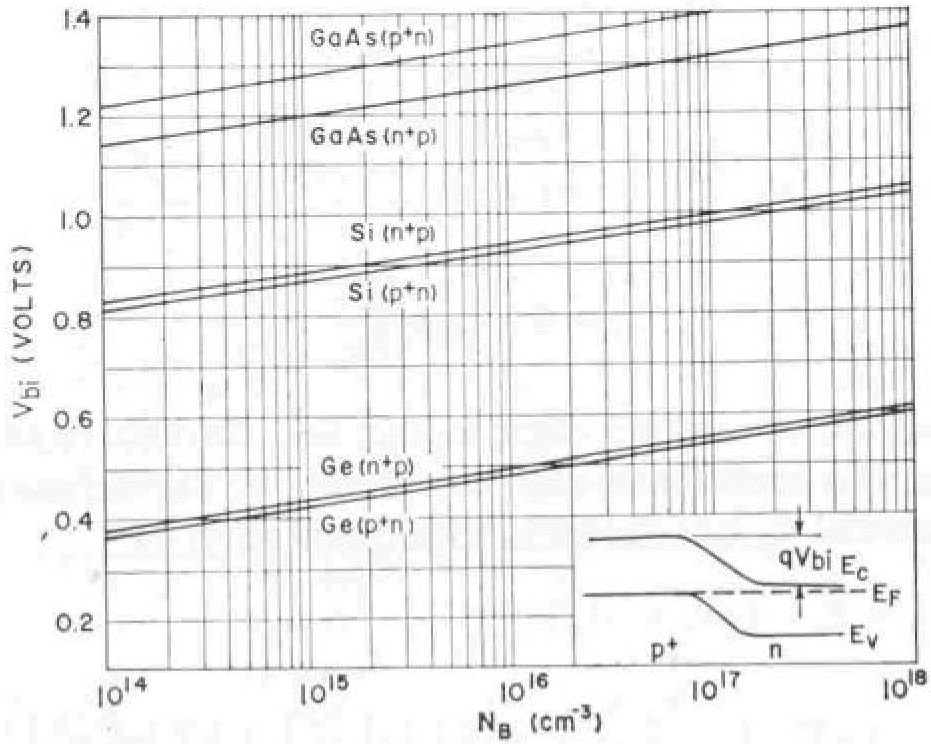

Fig. 8 Built-in potential for one-sided abrupt junctions in Ge, Si, and GaAs where p^+ is for heavily doped p side and n^+ is for heavily doped n side. The background doping N_B is for the impurity concentration of the lightly doped side.

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PN Junctions - Depletion Region (Neudeck p.36,40)

$$W = \left[\frac{2K_S\varepsilon_0}{q}(V_{bi} - V_A)\left(\frac{N_A + N_D}{N_A N_D}\right)\right]^{1/2}$$

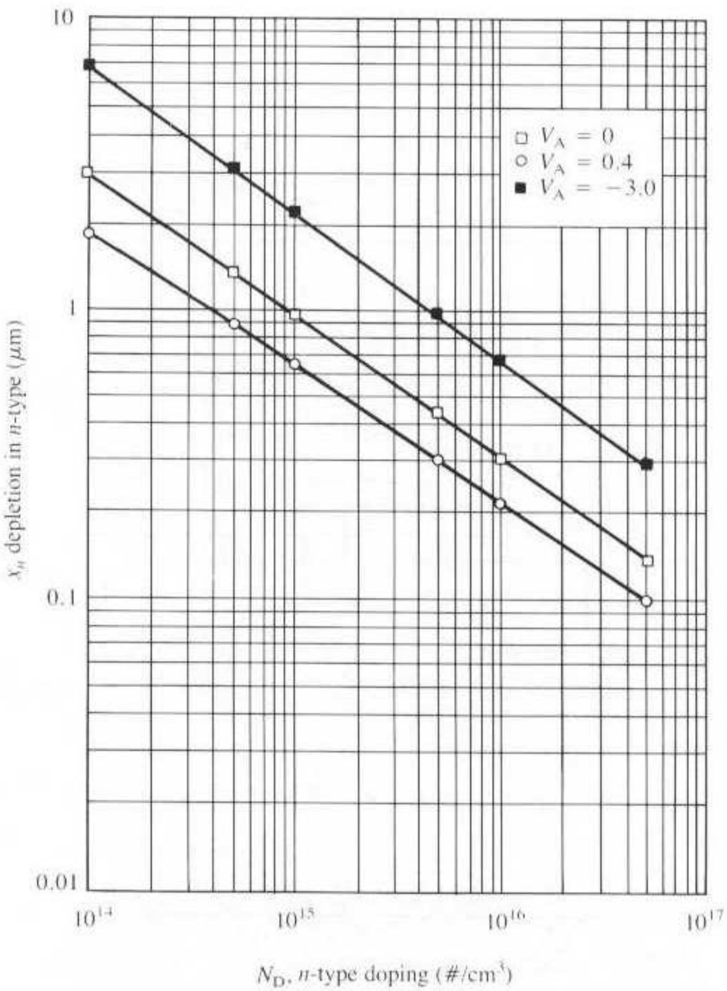

Fig. 2.9 n-depletion region for $V_A = 0$, 0.4, and -3.0 volts.

From course notes, and various textbooks, one can derive the depletion width. (Where Vbi is the built-in potential, Ks is the relative permittivity, ε is the permittivity of free space, Na is the acceptor concentration, and Nd is the donor concentration)

As the applied bias (Va) becomes more positive with respect to the n-type region, the Vbi barrier is overcome, and the depletion width becomes narrower. Conversely, as Va becomes more negative with respect to the n-type region, the depletion width will increase.

One can also see, as the doping of one side is much greater than the other, the depletion width depends on the lightly doped region.

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PN Junctions - Forward, Reverse Biasing (Neudeck p.38,39)

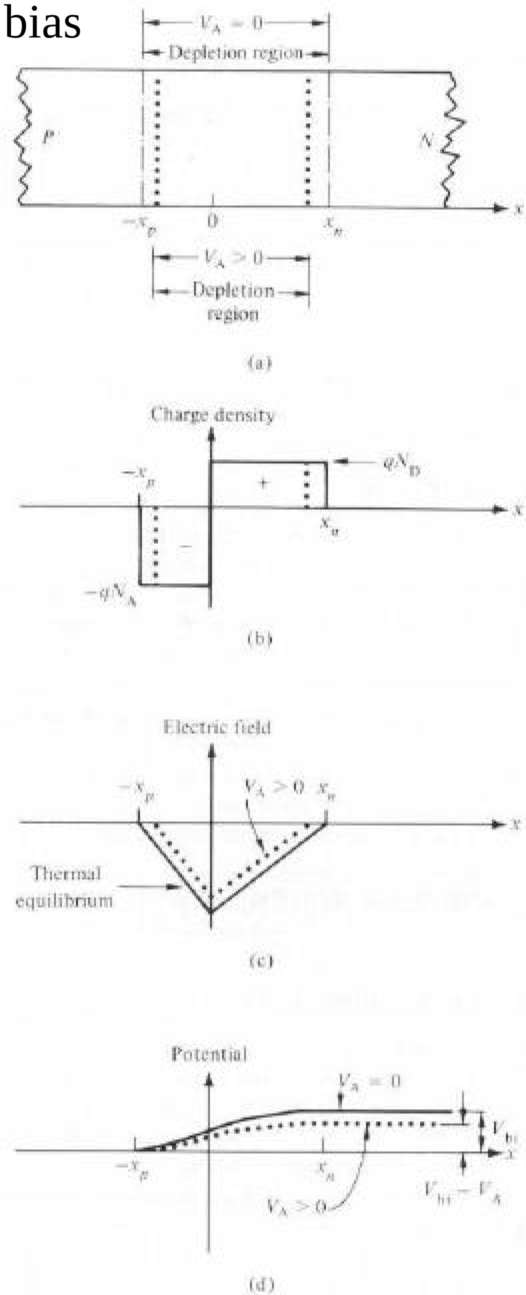
Forward bias

Depletion width narrows

Total charge decreases

E-field decreases

Potential decreases by amount of bias



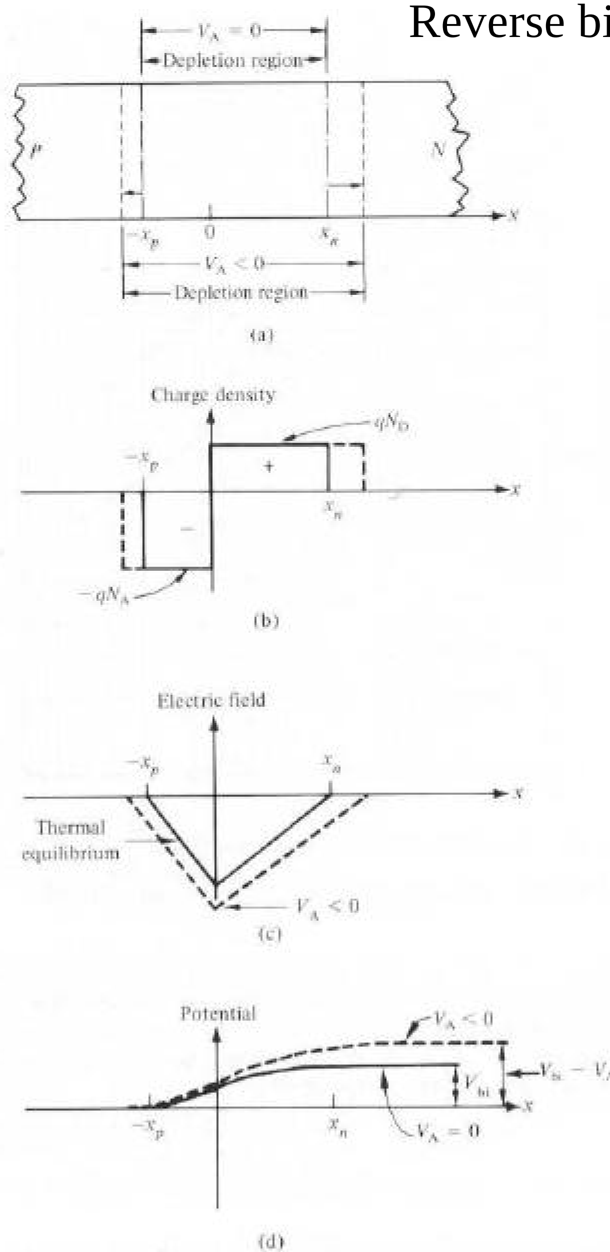
Reverse bias

Depletion width widens

Total charge increases

E-field increases

Potential increases by amount of bias



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PN Junctions - Thermal Equilibrium (Neudeck p.46)

•Jdrift - Jdiff = 0

•Density of states gives the number of free carriers available in the conduction band that are above qVbi energy

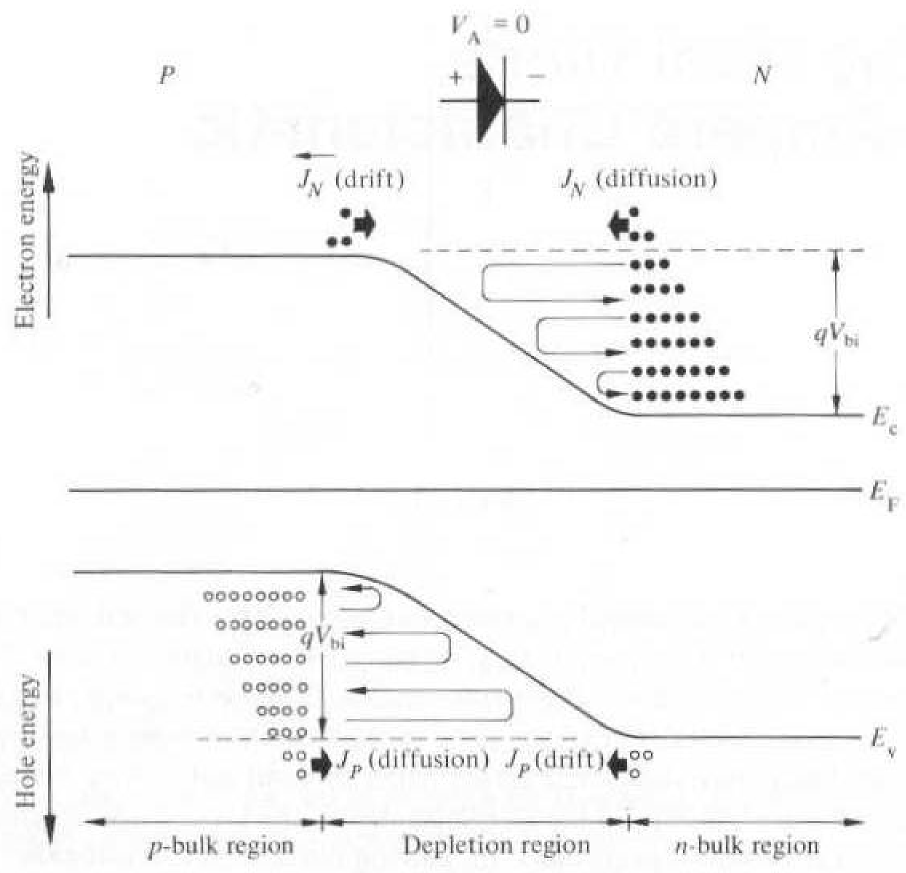

Fig. 3.1 Thermal equilibrium: energy band diagram and carrier flux.

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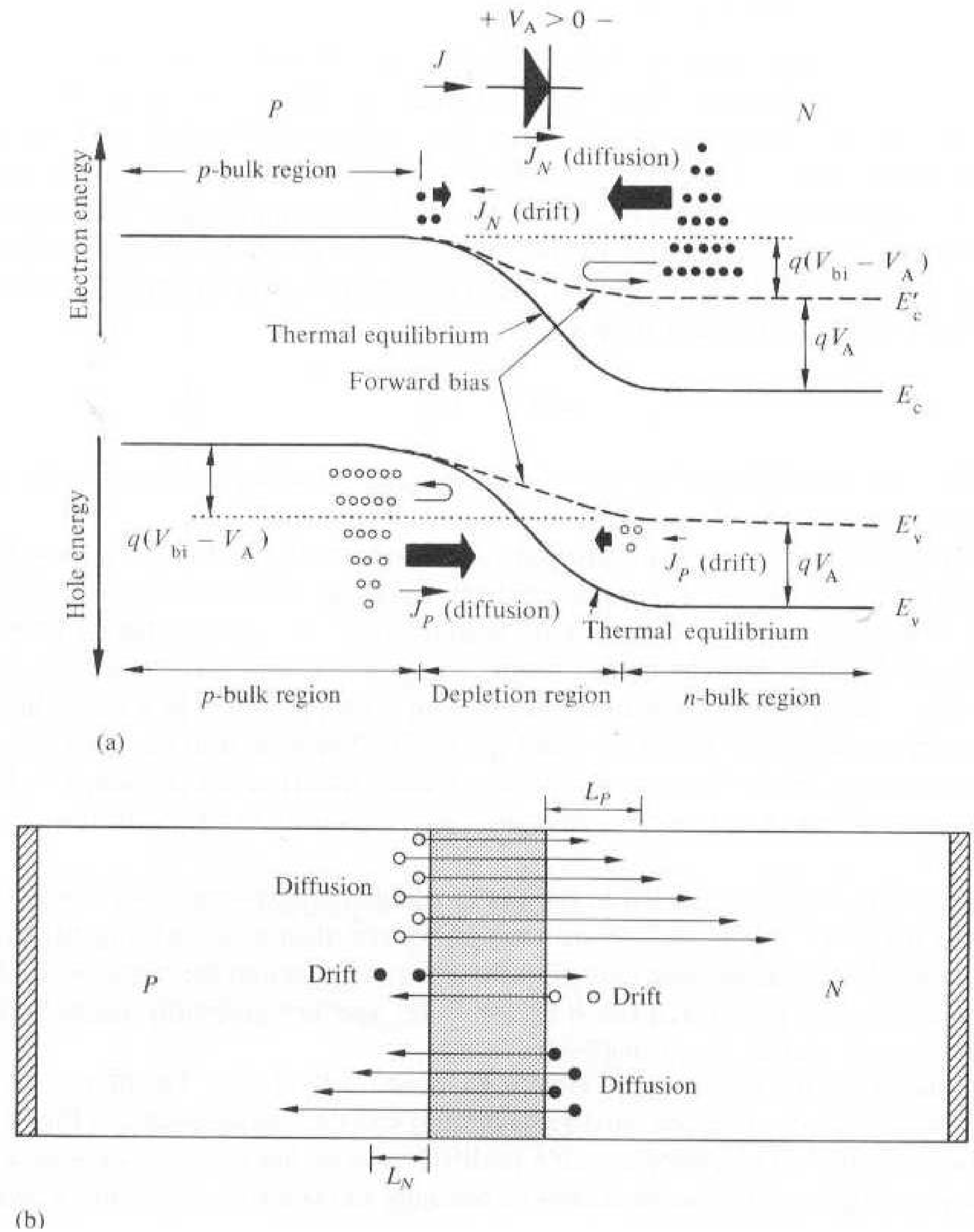
PN Junctions - Forward Bias (Neudeck p.50)



•Va is negative with respect to the p-type (or positive wrt the n-type region)

•The energy bands bend so that the qVa energy increases the amount of diffusion carriers available in the density of states.

The drift current remains constant, as the available carriers have not changed (electrons in the p-type region,
holes in the n-type region)

Forward bias current is therefor dependent on the number of majority carriers available in the conduction band, which is an exponential relationship. This is more than the thermal equilibrium condition.

Jdiff > Jdrift, so large positive current

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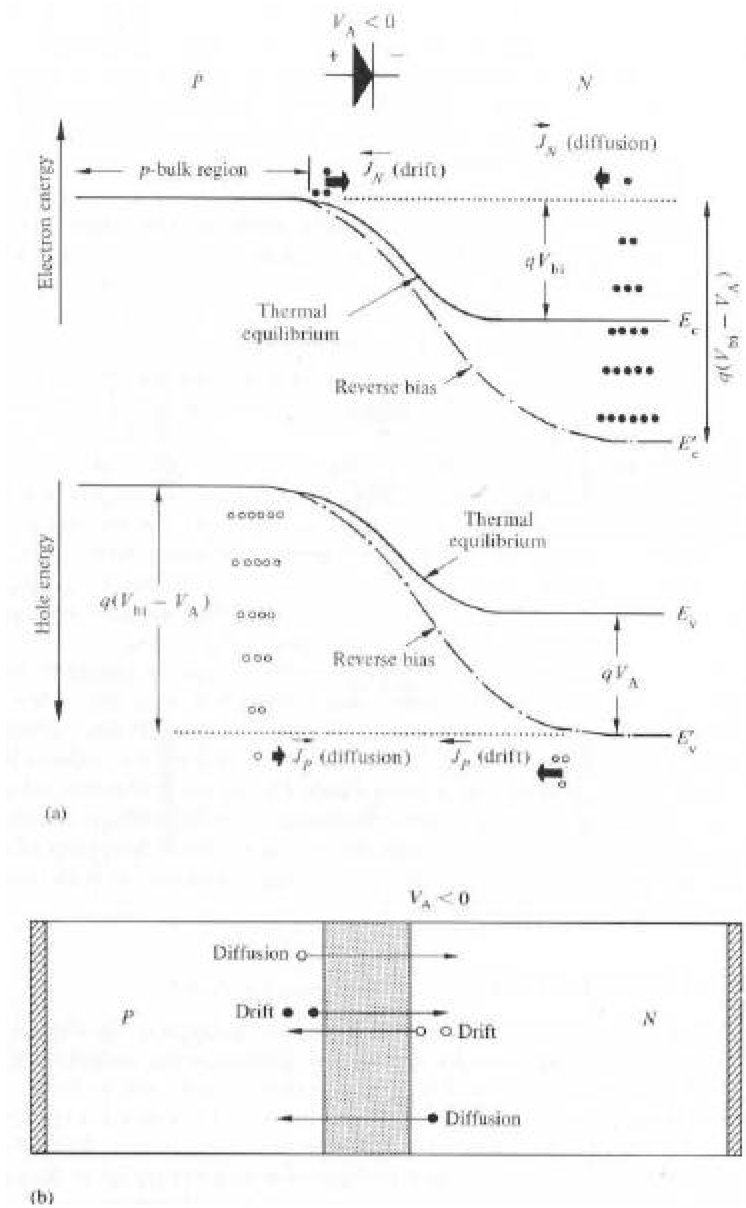
PN Junctions - Reverse Bias (Neudeck p.51)



•Va is positive with respect to the p-type (or negative wrt the n-type region)

•The energy bands bend so that the qVa energy decreases the amount of diffusion carriers available in the density of states.

•The drift current remains constant, as the available carriers have not changed (electrons in the p-type region, holes in the n-type region)

•Reverse bias current is therefor dependent on the number of majority carriers available in the conduction band, which is an exponential relationship. This is less than the thermal equilibrium condition.

Jdrift > Jdiff, so small negative current limited by minority carrier supply

Class 04: Device Physics I

PN Junctions - Junction Capacitance (Martin p.75-77)

To find the junction capacitance, start with the depletion width for an abrupt junction:

$$x_n = \left[\frac{2K_s\varepsilon_0(\Phi_0 + V_R)}{q}\frac{N_A}{N_D(N_A + N_D)}\right]^{1/2}$$

$$x_p = \left[\frac{2K_s\varepsilon_0(\Phi_0 + V_R)}{q}\frac{N_D}{N_A(N_A + N_D)}\right]^{1/2}$$

The charge in the depletion region (per cross sectional area) is the depletion width times the concentration of ionic charge (qN). For the p-type region, and assuming that Na >> Nd:

$$Q^- = Q^+ \cong [2qK_s\varepsilon_0(\Phi_0 + V_R)N_D]^{1/2}$$

The junction capacitance can be derived by differentiating Q wrt Vr:

$$C_j = \frac{dQ^+}{dV_R} = \left[\frac{qK_s\varepsilon_0}{2(\Phi_0 + V_R)}\frac{N_A N_D}{N_A + N_D}\right]^{1/2} = \frac{C_{j\text{-}0}}{\sqrt{1 + (V_R/\Phi_0)}}$$

$$C_{j\text{-}0} = \sqrt{\frac{qK_s\varepsilon_0}{2\Phi_0}\frac{N_A N_D}{N_A + N_D}}$$

For a one-sided diode (Na>>Nd):

$$C_j = \left[\frac{qK_s\varepsilon_0 N_D}{2(\Phi_0 + V_R)}\right]^{1/2} = \frac{C_{j\text{-}0}}{\sqrt{1 + (V_R/\Phi_0)}}$$

$$C_{j\text{-}0} = \sqrt{\frac{qK_s\varepsilon_0 N_D}{2\Phi_0}}$$

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PN Junctions - Diode Equation (Neudeck p.63-65)

$$J = q\left[\frac{D_N}{L_N}n_{p0} + \frac{D_P}{L_P}p_{n0}\right](e^{qV_A/kT} - 1)$$

Ideal or Shokley Diode Equation

Multiplying by the area of the junction (A) yields the total current

$$I = I_0(e^{qV_A/kT} - 1)$$

where the reverse saturation current has been defined as

$$I = qAn_i^2\left[\frac{D_N}{L_N N_A} + \frac{D_P}{L_P N_D}\right](e^{qV_A/kT} - 1)$$

$$I_0 = qA\left[\frac{D_N}{L_N}n_{p0} + \frac{D_P}{L_P}p_{n0}\right]$$

•Current proportional to the diode junction area and inversely proportional to doping (why you want lightly doped substrates)

•Reverse current dependent on the minority carrier diffusion coefficient (Dn,p), minority carrier diffusion length (Ln,p), and minority carrier concentration (n_p, p_n)

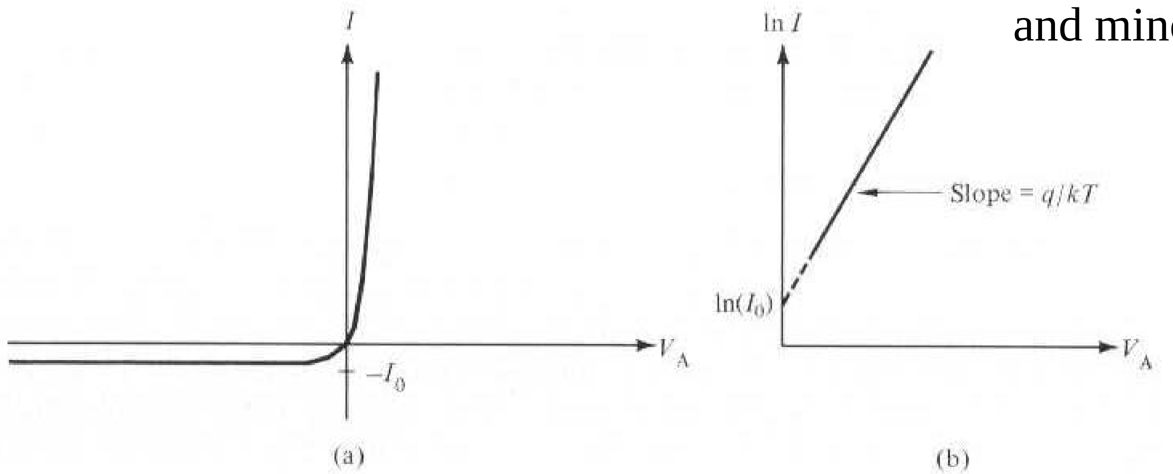

Fig. 3.10 *p-n* junction volt–ampere characteristics: (a) linear plot; (b) semilogarithmic plot.

Who cares?
Reverse diode leakage is related to off-state leakage of an IC