ECE 342
Electronic Circuits

Lecture 3
PN Junctions and Diodes

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Definitions

B: material dependent parameter = 5.4×10^{31} for Si
E_G: Bandgap energy = 1.12 eV
k: Boltzmann constant=8.62×10^{-5} ev/K
n_i: intrinsic carrier concentration
At T = 300 K, $n_i = 1.5 \times 10^{10}$ carriers/cm^3
J_p: hole current density A/m^2
J_n: electron current density A/m^2
q: electron charge
D_p: Diffusion constant (diffusivity) of holes
D_n: Diffusion constant (diffusivity) of electrons

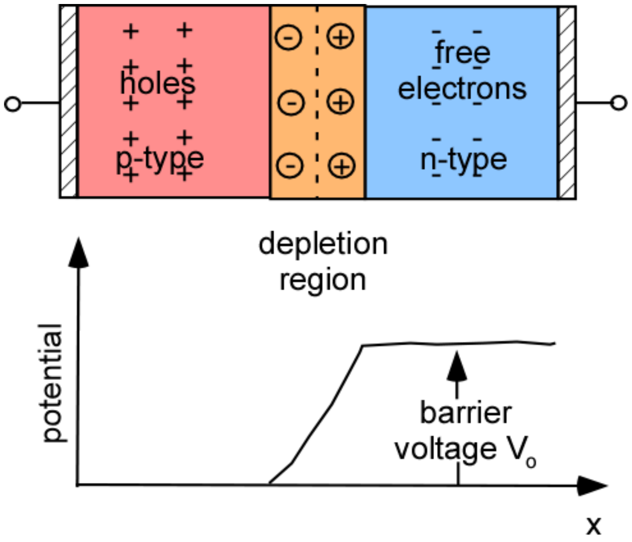
μ_p: mobility for holes = 480 cm^2 /V sec
μ_n: mobility for electrons = 1350 cm^2 /V sec

N_D: concentration of donor atoms
n_{no}: concentration of free electrons at thermal equilibrium

N_A: concentration of acceptor atoms
p_{po}: concentration of holes at thermal equilibrium

$$\text{Einstein Relation}: \frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{q} = V_T : \textit{thermal voltage}$$

PN Junction



- **When a p material is connected to an n-type material, a junction is formed**
  - Holes from p-type diffuse to n-type region
  - Electrons from n-type diffuse to p-type region
  - Through these diffusion processes, recombination takes place
  - Some holes disappear from p-type
  - Some electrons disappear from n-type

A depletion region consisting of bound charges is thus formed
Charges on both sides cause electric field ➔ potential = V_o

PN Junction

- **Potential acts as <u>barrier</u> that must be overcome for holes to diffuse into the n-region and electrons to diffuse into the p-region**
- **Open circuit: No external current**

Junction built-in voltage

From principle of detailed balance and equilibrium we get:

$$V_o = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

For Si, V_o is typically 0.6V to 0.8V

Charge equality in depletion region gives:

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

A: cross-section of junction
x_p: width in p side
x_n : width in n side

ε_s : silicon permittivity
$\varepsilon_s = 11.7\varepsilon_o = 1.04\times 10^{-8}$ F/m

$$\frac{x_n}{x_p} = \frac{N_A}{N_D}$$

$$W_{dep} = x_n + x_p = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)V_o}$$

Example

Find the barrier voltage across the depletion region of a silicon diode at T = 300 K with N_D=10^{15}/cm^3 and N_A=10^{18}/cm^3.

Use $$V_o = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

@ 300K,

$$n_i = 1.5\times10^{10}/\text{cm}^3$$

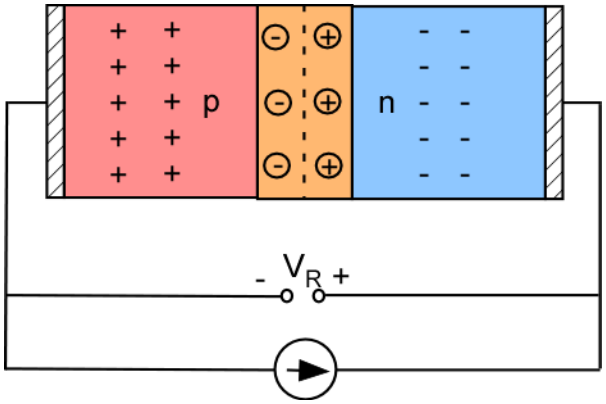
$$V_T = 0.026\text{ V}$$

$$V_o = \psi_o = 0.026\ln\left(\frac{10^{18}\cdot10^{15}}{(1.5)^2\times10^{20}}\right) = 0.026\ln\left[\frac{10^{13}}{2.25}\right]$$

$$V_o = \psi_o = 0.026\times29.12 = 0.7571\text{ volts}$$

$$V_o = \psi_o = 0.7571\text{ volts}$$

PN Junction under Reverse Bias



- **When a reverse bias is applied**
  - Transient occurs during which depletion capacitance is charged to new bias voltage
  - Increase of space charge region
  - Diffusion current decreases
  - Drift current remains constant
  - Barrier potential is increased
  - A steady state is reached
  - After transient: steady-state reverse current = I_S-I_D (I_D is very small) ➔ reverse current ~ I_S ~10^{-15} A

Under reverse bias the current in the diode is negligible

Depletion Layer Stored Charge

$$q_j = q_N = qN_D x_n A$$

A: cross section area

q_j: stored charge

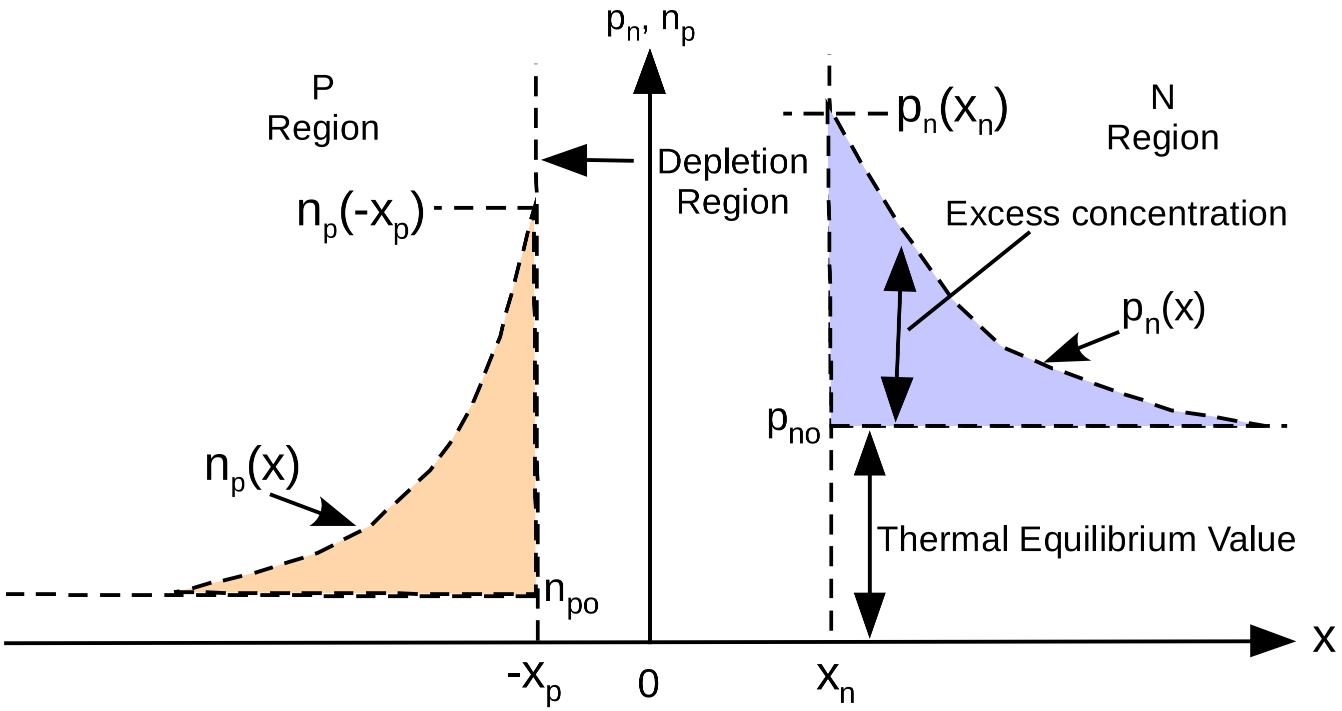
Let W_{dep}= depletion-layer width

$$q_j = q\frac{N_A N_D}{N_A + N_D} A W_{dep}$$

The total voltage across the depletion layer is $V_o + V_R$

$$W_{dep} = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_o + V_R)}$$

Forward-Biased Junction Carrier Distribution



$N_A >> N_D$

Barrier voltage is now lower than V_o

In steady state, concentration profile of excess minority carriers remains constant

Forward-Biased PN Junction

Diode equation: $I_D = I_S\left(e^{V/nV_T} - 1\right)$

$$I_S = Aqn_i^2\left(\frac{D_p}{L_pN_D} + \frac{D_n}{L_nN_A}\right)$$

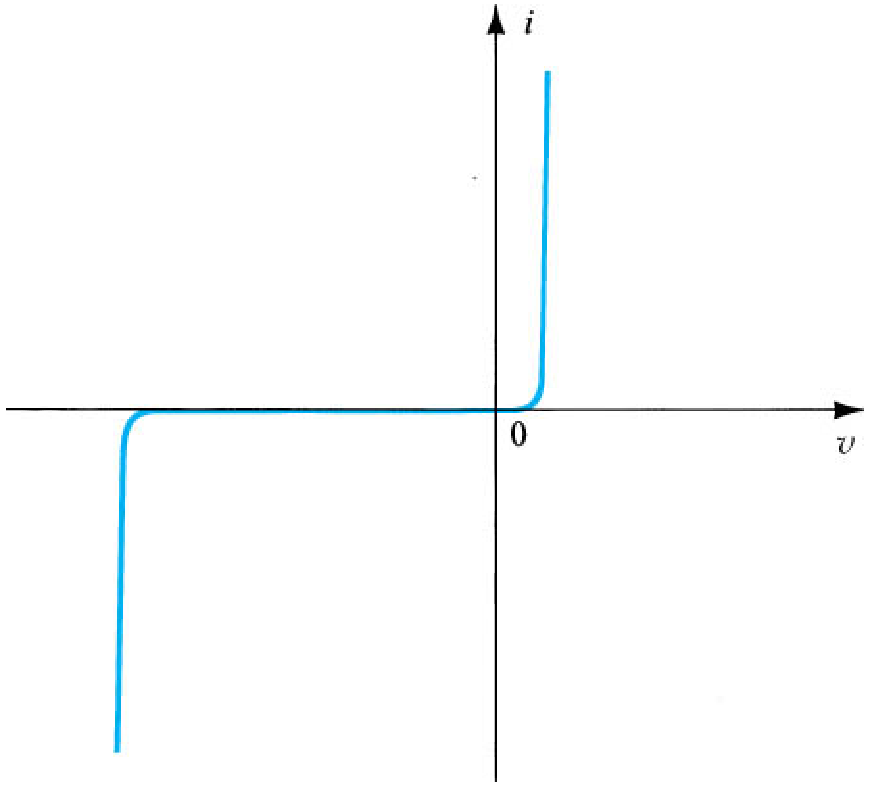
since n_i^2 is a strong function of temperature; thus I_s is a strong function of temperature

n has a value between 1 and 2. Diodes made using standard IC process have $n=1$; discrete diodes have $n=1$

In general, assume *n=1*

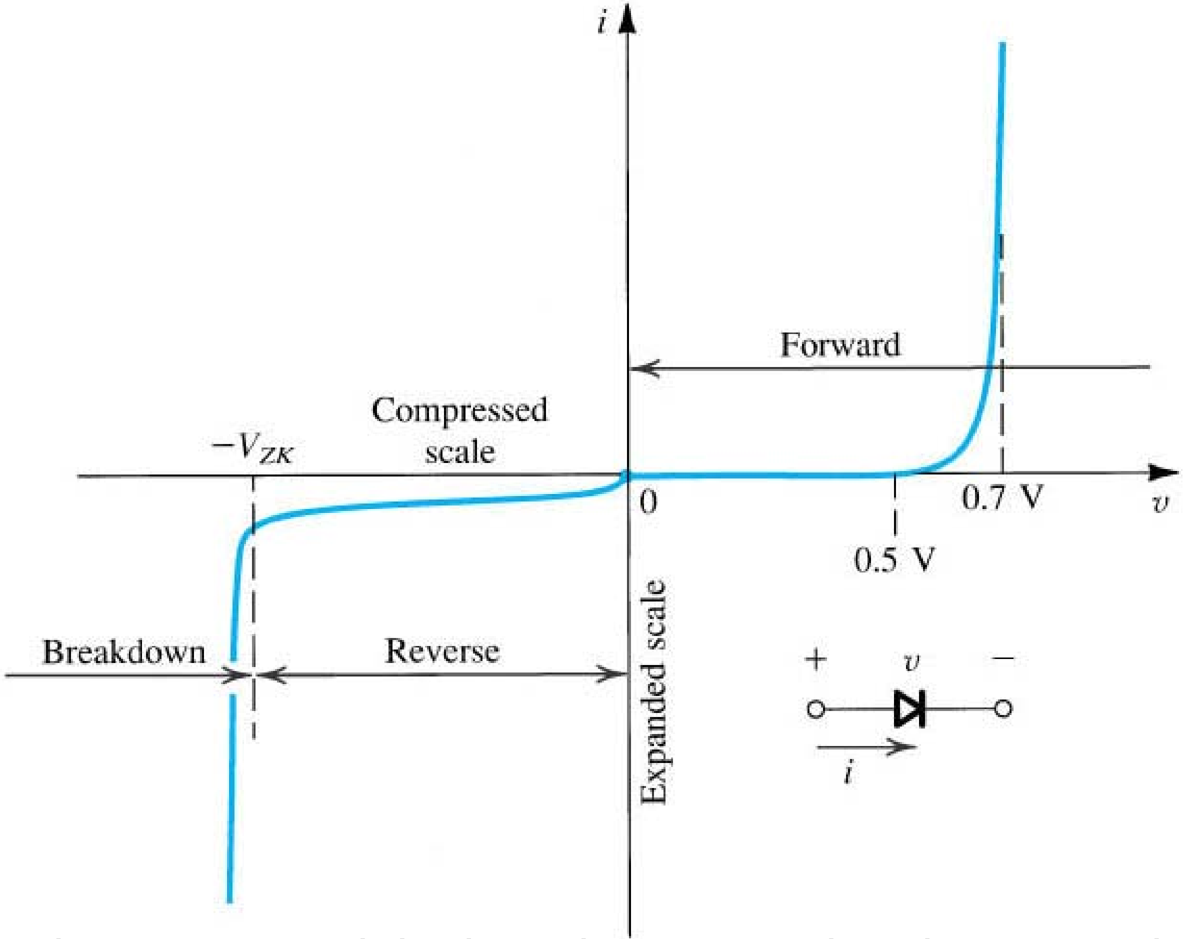
If $V \gg V_T$, we can use $I_D \approx I_S e^{V/V_T}$

Diode Characteristics



- **Three distinct regions**
  - The forward-bias region, determined by $v > 0$
  - The reverse-bias region, determined by $v < 0$
  - The breakdown region, determined by $v < -V_{ZK}$

Diode I-V Relationship



Breakdown

- Electric field strong enough in depletion layer to break covalent bonds and generate electron-hole pairs. Electrons are then swept by E-field into the n-side. Large number of carriers for a small increase in junction voltage