

Many of the figures and tables in this are taken from the book *Semiconductor Physics and Devices* by Donald A. Neamen

## 1 Crystal Structure

There are 3 types of crystals: Crystalline (Single), Polycrystalline, and Amorphous.

### 1.1 Primitive and Unit Cell

A unit cell is a small volume of a crystal that can be used to represent the entire crystal. The primitive unit cell is the smallest cell that can do this.

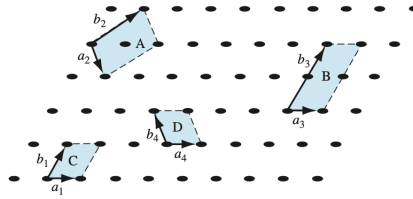


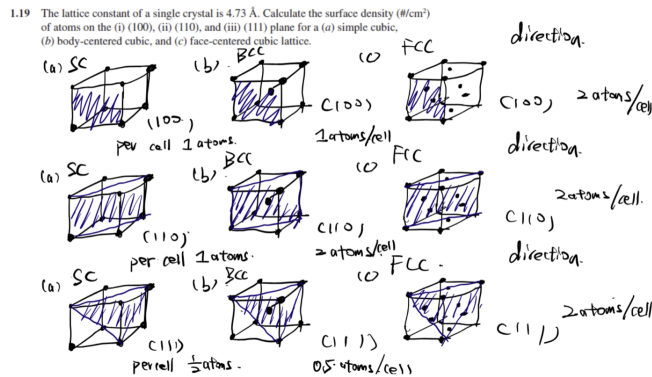
Figure 1.3 | Two-dimensional representation of a single-crystal lattice showing various possible unit cells.

Every point can be found using the vector  $\bar{r} = p\bar{a} + q\bar{b} + s\bar{c}$

### 1.2 Basic Crystal Structure

Miller indices are given by

$$\left(\frac{1}{p}, \frac{1}{q}, \frac{1}{s}\right) \cdot LCM(p, q, s)$$



Area of each cell

$$(100) = a^2, (110) = \sqrt{2}a^2, (111) = \frac{\sqrt{3}}{2}a^2$$

## 2 Quantum Mechanics

### 2.1 Wave Particle Duality

de Broglie wavelength

$$\lambda = \frac{h}{p}$$

### 2.2 Uncertainty Principle

The more we know about one aspect of particle the less we know about another

$$\Delta x \Delta p \geq \hbar$$

$$\Delta E \Delta t \geq \hbar$$

## 2.3 Schrodinger's Equation

$$-\frac{\hbar^2}{2m} \cdot \frac{\partial^2 \Psi(x, t)}{\partial x^2} + V(x) \Psi(x, t) = j\hbar \frac{\partial \Psi(x, t)}{\partial t}$$

We can also say  $\Psi(x, t) = \Psi(x)\Phi(t)$ . The equation then becomes

$$-\frac{\hbar^2}{2m} \frac{1}{\Psi(x)} \frac{\partial^2 \Psi(x)}{\partial x^2} + V(x) = j\hbar \frac{1}{\Phi(t)} \frac{\partial \Phi(t)}{\partial t}$$

$\Psi(x)$  and  $\partial \Psi(x)/\partial x$  must be finite, single-valued, and continuous. Looking at only the time dependent part of the equation we can set the whole thing equal to a constant  $\eta$  that is equal to the total energy of the particle. We get an equation that is just oscillating in time.

$$\eta = j\hbar \frac{1}{\Phi(t)} \frac{\partial \Phi(t)}{\partial t}$$

$$\Phi(t) = e^{-j(\eta/\hbar)t} = e^{-j\omega t}$$

Then we are also able to get the time-independent Schrodinger equation.

$$\frac{\partial^2 \Psi(x)}{\partial x^2} + \frac{2m}{\hbar^2} [E - V(x)] \Psi(x) = 0$$

### 2.3.1 Free electron

$V(x) = 0$ .

$$\Psi(x) = A \exp(jkx) + B \exp(-jkx)$$

Where  $k \equiv \frac{\sqrt{2mE}}{\hbar}$

### 2.3.2 Infinite Potential Well

$$\Psi(x) = \sqrt{\frac{2}{a}} \sin k_n x$$

$$k_n^2 = \frac{2mE_n}{\hbar^2} = \frac{n^2 \pi^2}{a^2}$$

$$E = E_n = \frac{\hbar^2 n^2 \pi^2}{2ma^2}$$

Where  $a$  is the width of the potential well.

### 2.3.3 Step Potential Function

At  $x = 0$  there is a finite step potential to an energy barrier. Region I has 0 potential while Region II is at  $V_0$ .

$$\Psi_1(x) = A_1 e^{jkx} + B_2 e^{-jkx}$$

$$\Psi_2(x) = A_2 e^{-k_2 x} + B_2 e^{k_2 x}$$

where

$$k_2 = \sqrt{\frac{2m(V_0 - E)}{\hbar^2}}$$

Plugging in for all boundary conditions and ensuring the wave function is finite and continuous we get that

$$\Psi_2(x) = A_2 e^{-k_2 x}$$

We also find that

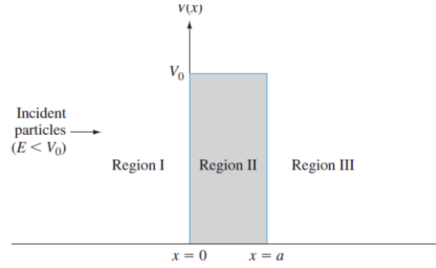
$$B_1 = \frac{-k_2 + 2jk_1k_2 - k_1^2}{k_2^2 + k_1^2} \cdot A_1$$

$$A_2 = \frac{2k_1(k_1 - jk_2)}{k_2^2 + k_1^2} \cdot A_2$$

The reflection coefficient is also found

$$R = \frac{B_1 B_1^*}{A_1 A_1^*} = \frac{(k_2^2 - k_1^2) + 4k_1^2 k_2^2}{(k_2^2 + k_1^2)^2}$$

### 2.3.4 Potential Barrier



3 solutions for region I, II, and III.

$$\Psi_1(x) = A_1 e^{jk_1 x} + B_1 e^{-jk_1 x}$$

$$\Psi_2(x) = A_2 e^{k_2 x} + B_2 e^{-k_2 x}$$

$$\Psi_3(x) = A_3 e^{jk_1 x} + B_3 e^{-jk_1 x}$$

where

$$k_1 = \sqrt{\frac{2mE}{\hbar^2}}$$

$$k_2 = \sqrt{\frac{2m}{\hbar^2}(V_0 - E)}$$

Transmission is given by

$$T \approx 16 \frac{E}{V_0} \left(1 - \frac{E}{V_0}\right) e^{-2k_2 a}$$

## 2.4 Energy of electron (Hydrogen Model)

$$E_n = \frac{-m_0 e^4}{(4\pi\epsilon_0)^2 2\hbar^2 n^2}$$

If n is bigger then the energy is less negative meaning its easier to remove an electron.

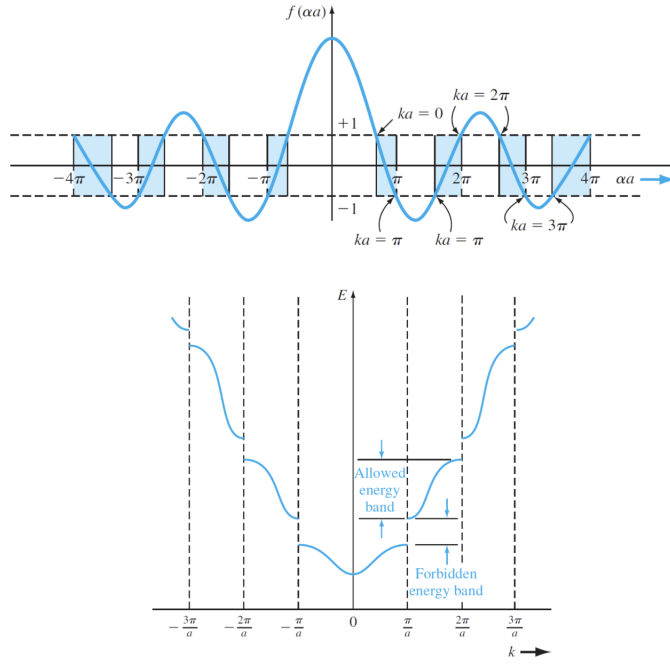
# 3 Quantum Theory of Solids

## 3.1 Kronig Penney Model

$$\Psi(x) = u(x) e^{jkx}$$

Where  $u(x)$  is a periodic step function. Plugging it back in and solving for the boundary conditions you get

$$P' \frac{\sin \alpha a}{\alpha a} + \cos \alpha a = \cos ka$$



### 3.2 Density of States

$$g_T(k)dk = \frac{\pi k^2 dk}{\pi^3} a^3$$

Convert this to in terms of energy using  $k^2 = \frac{2mE}{\hbar^2}$

$$g_T(E) = \frac{4\pi a^3}{h^3} (2m)^{3/2} \sqrt{E}$$

$$N = \int_{E_0}^E g_T(E) dE$$

For the conduction and valence band

$$g_c(E) = \frac{4\pi}{h^3} (2m_n^*)^{3/2} \sqrt{E - E_c}$$

$$g_v(E) = \frac{4\pi}{h^3} (2m_p^*)^{3/2} \sqrt{E_v - E}$$

### 3.3 Effective Mass

$$F_{ext} = m^* a$$

$$\frac{1}{\hbar^2} \frac{d^2 E}{dk^2} = \frac{1}{m^*}$$

$$a = \frac{-eE}{m_n^*}$$

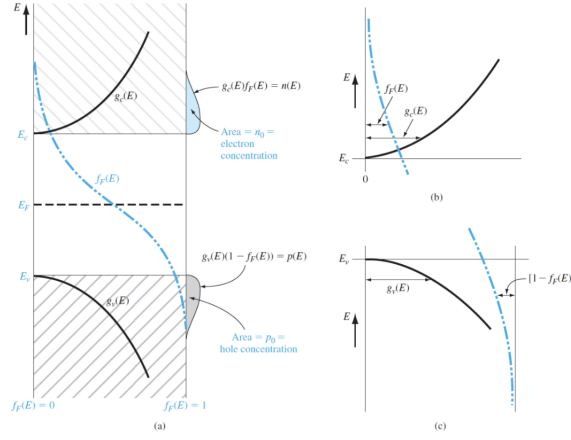
### 3.4 Probabilty and Density Distribution

The Fermi-Dirac distribution is given by

$$f_F(E) = \frac{1}{1 + \exp(\frac{E - E_f}{kT})}$$

Maxwell-Boltzmann Approximation

$$f_F(E) = \exp[\frac{-(E - E_f)}{kt}]$$



## 4 Semiconductors in Equilibrium

$$n(E) = g_c(E)f_F(E)$$

$$p(E) = g_v(E)(1 - f_F(E))$$

The equilibrium concentration of electrons in CB is

$$n_o = N_c \exp\left[\frac{-(E_c - E_f)}{kT}\right]$$

$$N_c \equiv 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$$

Holes:

$$p_o = N_v \exp\left[\frac{-(E_f - E_v)}{kT}\right]$$

$$N_v \equiv 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2}$$

$N_c$  can be found using this relationship for different temperatures

$$N'_c = N_c \left(\frac{T}{300}\right)^{3/2}$$

### 4.1 Intrinsic Carrier Concentration

$$n_i = N_c \exp\left[\frac{-(E_c - E_{Fi})}{kT}\right] = n_o$$

$$p_i = N_v \exp\left[\frac{-(E_{Fi} - E_v)}{kT}\right] = p_o = n_i$$

$$n_i p_i = n_i^2 = N_c N_v \exp\left[\frac{-E_g}{kT}\right]$$

$$n_o p_o = n_i^2$$

The fermi level is given by

$$E_{Fi} = E_{\text{midgap}} + \frac{3}{4}kT \ln\left(\frac{m_p^*}{m_n^*}\right)$$

### 4.2 Extrinsic Semiconductor

If we already know  $E_{Fi}$  and  $n_i$  it may be easier to use

$$n_o = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right]$$

$$p_o = n_i \exp\left[\frac{-(E_F - E_{Fi})}{kT}\right]$$

### 4.3 Donors and Acceptors

The concentration of electrons occupying the donor level is given by

$$n_d = \frac{N_d}{1 + \frac{1}{2} \exp(\frac{E_d - E_f}{kT})}$$

Where  $N_d$  is the concentration of donor atoms. The concentration at the donor level can also be expressed as

$$n_d = N_d - N_d^+$$

Where  $N_d^+$  is the concentration of ionized donors. We can do the same thing for acceptors.

$$p_a = \frac{N_a}{1 + \frac{1}{g} \exp(\frac{E_f - E_a}{kT})} = N_a - N_a^-$$

Where  $1/g = 1/2$ . In the case  $E_d - E_f \gg kT$

$$n_d \approx 2N_d \exp[\frac{-(E_d - E_f)}{kT}]$$

## 5 Charge Neutrality

We have a compensated semiconductor where both  $n_d$  and  $n_a$  are in the same region. Then net charge density = 0.

$$\begin{aligned} n_0 + N_a^- &= p_0 + N_d^+ \\ n_0 + (N_a - p_a) &= p_0 + (N_d - n_d) \end{aligned}$$

If we assume complete ionization

$$n_0 + N_a = p_0 + N_d$$

The electron concentration can then be determined by

$$n_0 = \frac{N_d - N_a}{2} + \sqrt{(\frac{N_d - N_a}{2})^2 + n_i^2}$$

Similarly the holes concentration is

$$p_0 = \frac{N_a - N_d}{2} + \sqrt{(\frac{N_a - N_d}{2})^2 + n_i^2}$$

### 5.1 Position of Fermi Level

$$E_c - E_F = kT \ln(\frac{N_c}{n_0})$$

In n-type

$$E_c - E_F = kT \ln \frac{N_c}{N_d}$$

or for compensated

$$E_c - E_F = kT \ln \frac{N_c}{N_d - N_a}$$

$$E_F - E_{Fi} = kT \ln \frac{n_0}{n_i}$$

If a semiconductor is fully compensated i.e.  $N_a = N_d$  then  $n_0 = n_i$  and  $E_F = E_{Fi}$ .

For p-type

$$E_F - E_v = kT \ln \frac{N_v}{p_o}$$

$$E_F - E_v = kt \ln \frac{N_v}{N_a}$$

$$E_{Fi} - E_F = kT \ln \frac{p_o}{n_i}$$

## 6 Carrier Transport

The two main sources of the movement of charge is drift and diffusion. The equations describing drift are

$$J_{drf} = \rho v_d$$

$$F = eE = m_{cp}^* a$$

We encapsulate everything in a mobility constant so then our equation becomes

$$J = e(\mu_n n + \mu_p p)E$$

This mobility is given by

$$\mu_p = \frac{e}{m_{cp}^*} \tau_{cp}$$

$$\mu_n = \frac{e}{m_{cn}^*} \tau_{cn}$$

Where  $\tau$  is the main collision time. The two main impedances to movement is impurity and lattice scattering which can be represented with the equation

$$\frac{1}{\mu} = \frac{1}{\mu_I} + \frac{1}{\mu_L}.$$

### 6.1 Conductivity

We can simply find the conduvivity from the drift equation

$$J = e(\mu_n n + \mu_p p)E = \sigma E.$$

Giving us the equation for resitivity as well

$$\rho = \frac{1}{\sigma} = \frac{1}{e(\mu_n n + \mu_p p)}.$$

In the case of complete ionization it is often written just as a function of the majority carriers

$$\sigma \approx e\mu_p N_a \approx \frac{1}{\rho}.$$

### 6.2 Carrier Difussion

Diffusion is the other source of current in a semiconductor.

$$J = ev_{th} l \frac{dn}{dx}$$

We turn this into a constant

$$J_{n|dif} = eD_n \frac{dn}{dx}$$

$$J_{p|dif} = eD_p \frac{dp}{dx}$$

We can combine all of these contributing factors to current into one equation

$$J = eD_n \nabla n - eD_p \nabla p + e\mu_n n E + e\mu_p p E.$$

### 6.3 Impurity Distribution

When we have nonuniform doping we can find the E field to be

$$E_x = - \left( \frac{kT}{e} \right) \frac{1}{N_d(x)} \frac{dN_d(x)}{dx}$$

which also then gives us the Einstein relation

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{e}.$$

## 7 Nonequilibrium Processes

### 7.1 Carrier Generation and Recombination

$$G_{n0} = G_{p0} = R_{p0} = R_{n0}$$

When we have generation and recombination the concentrations become

$$\begin{aligned} n &= n_0 + \delta n \\ p &= p_0 + \delta p \end{aligned}$$

and we must note that

$$np \neq n_0 p_0 = n_i^2.$$

We also then have the equations for excess carriers in n-type

$$R'_n = R'_p = \frac{\delta n(t)}{\tau_{p0}}$$

and in p-type

$$R'_n = R'_p = \frac{\delta n(t)}{\tau_{n0}}.$$

### 7.2 Ambipolar Transport

$$\boxed{D' \frac{\partial^2(\delta n)}{\partial x^2} + \mu' E \frac{\partial(\delta n)}{\partial x} + g - R = \frac{\partial(\delta n)}{\partial t}}$$

Where

$$D' = \frac{D_n D_p (n + p)}{D_n n + D_p p}$$

and

$$\mu' = \frac{\mu_n \mu_p (p - n)}{\mu_n n + \mu_p p}.$$

If we want to find out how fast charge neutrality is achieved we find the dielectric relaxation time constant

$$\tau_d = \frac{\epsilon}{\sigma}$$

### 7.3 Quasi Fermi Level

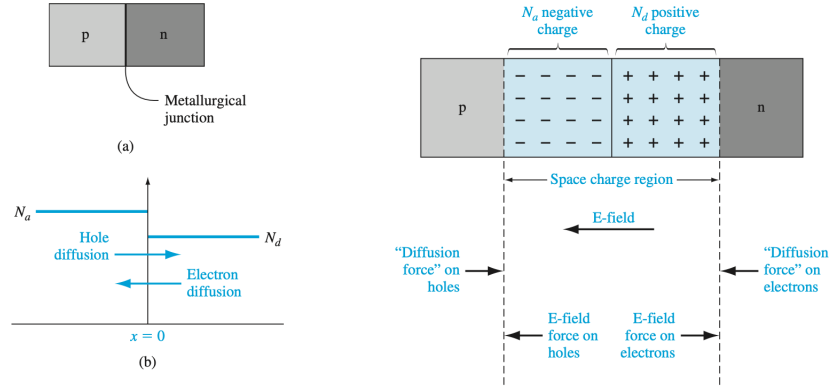
$$\boxed{n_0 + \delta n = n_i \exp \left( \frac{E_{Fn} - E_{Fi}}{kT} \right)}$$

$$\boxed{p_0 + \delta p = n_i \exp \left( \frac{E_{Fi} - E_{Fp}}{kT} \right)}$$



## 8 PN Junction

### 8.1 Basic Structure



### 8.2 Zero Bias

The built in voltage is

$$V_{bi} = \frac{kT}{e} \ln \left( \frac{N_a N_d}{n_i^2} \right) = V_t \ln \left( \frac{N_a N_d}{n_i^2} \right)$$

and the E field is described by

$$E = \frac{-eN_a}{\epsilon_s} (x_a + x_p) \text{ and } \frac{-eN_d}{\epsilon_s} (x_n - x).$$

This then gives us the relationship at the junction must be

$$N_a x_p = N_d x_n.$$

We can find for the space charge width

$$\begin{aligned} x_n &= \left[ \frac{2\epsilon_s V_{bi}}{e} \left( \frac{N_a}{N_d} \right) \left( \frac{1}{N_a + N_d} \right) \right]^{1/2} \\ x_p &= \left[ \frac{2\epsilon_s V_{bi}}{e} \left( \frac{N_d}{N_a} \right) \left( \frac{1}{N_a + N_d} \right) \right]^{1/2} \\ W &= x_n + x_p = \left[ \frac{2\epsilon_s V_{bi}}{e} \left( \frac{N_a + N_d}{N_a N_d} \right) \right]^{1/2} \end{aligned}$$

### 8.3 Reverse Bias

In reverse bias the applied voltage acts in the same direction as the built in voltage

$$V_{total} = V_{bi} + V_R.$$

The depletion width then becomes

$$W = \left[ \frac{2\epsilon_s (V_{bi} + V_R)}{e} \left( \frac{N_a + N_d}{N_a N_d} \right) \right]^{1/2}$$

and

$$\begin{aligned} E_{max} &= - \left[ \frac{2e(V_{bi} + V_R)}{\epsilon_s} \left( \frac{N_a N_d}{N_a + N_d} \right) \right]^{1/2} \\ E_{max} &= \frac{-2(V_{bi} + V_R)}{W}. \end{aligned}$$

## 8.4 Junction Capacitance

The capacitance per unit area is

$$C' = \frac{dQ'}{dV_R}$$

$$C' = \frac{e\epsilon_s N_a N_d}{2(V_{bi} + V_R)(N_a + N_d)}^{1/2}$$

which is equivalent to the standard capacitance equation

$$C' = \frac{\epsilon_s}{W}.$$

## 8.5 One Sided Junction

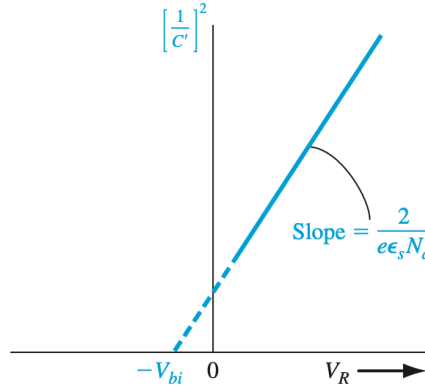
If we have one dominant much greater than the other for example  $N_a \gg N_d$  the width becomes

$$W \approx \left[ \frac{2\epsilon_s}{e} (V_{bi} + V_R) \frac{1}{N_d} \right]^{1/2}$$

Similarly the junction capacitance reduces to

$$C' \approx \left[ \frac{e\epsilon_s}{2} \frac{N_d}{V_{bi} + V_R} \right]^{1/2}.$$

If we have an abrupt junction the following graph applies



**Figure 7.11**  $(1/C')^2$  versus  $V_R$  of a uniformly doped pn junction.

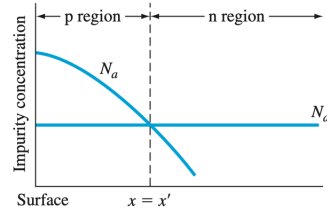
## 8.6 Junction Breakdown

When we reverse bias above a threshold voltage our junction goes into breakdown and an avalanche effect occurs

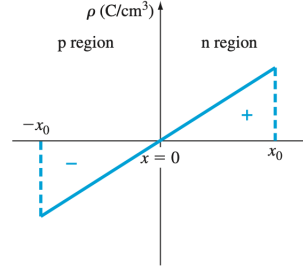
$$V_B = \frac{\epsilon_s E_{crit}^2}{2eN_B}$$

where  $N_B$  is the concentration of the low doped region of the one sided junction.

## 8.7 Nonuniformly Doped Junctions



**Figure 7.16** | Impurity concentrations of a pn junction with a nonuniformly doped p region.



**Figure 7.17** | Space charge density in a linearly graded pn junction.

Solving for  $\frac{dE}{dx} = \frac{\rho(x)}{\epsilon_s} = \frac{eax}{\epsilon_s}$  we find

$$\Phi(x_0) = V_{bi} = \frac{2}{3} \frac{eax_0^3}{\epsilon_s}$$

Subsequently

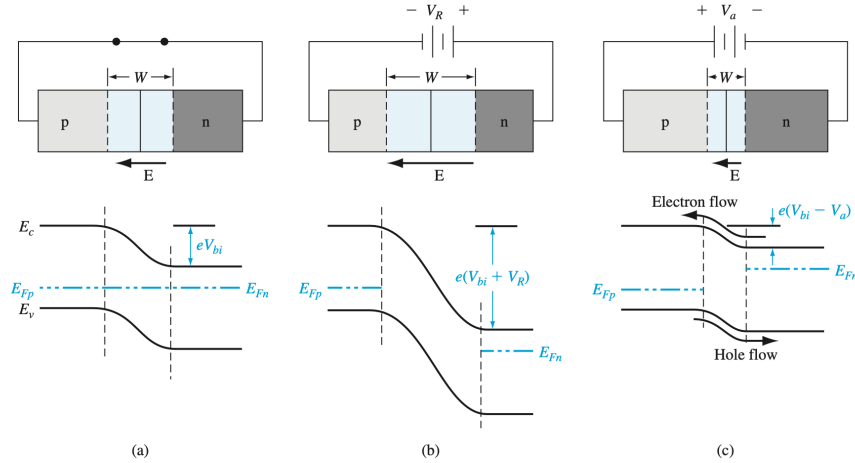
$$x_0 = \left[ \frac{3}{2} \frac{\epsilon_s}{ea} (V_{bi} + V_R) \right]^{1/3}$$

$$C' = \left[ \frac{ea\epsilon_s^2}{12(V_{bi} + V_R)} \right]^{1/3}$$

Where  $a$  is the gradient of net impurity concentration.

## 9 PN Junction Diode

Now we examine diodes in both forward and reverse bias.



The concentration of minority electrons in relation to the majority carriers is

$$n_{p0} = n_n \exp\left(\frac{-eV_{bi}}{kT}\right)$$

Then by applying a forward bias to this we obtain the minority carrier concentration at the edge of the depletion region

$$n_p = n_{p0} \exp\left(\frac{eV_a}{kT}\right)$$

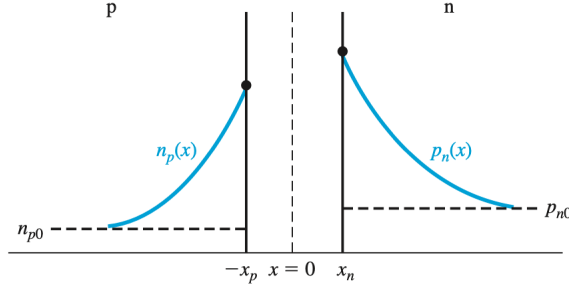
$$p_n = p_{n0} \exp\left(\frac{eV_a}{kT}\right)$$

The minority concentration increases because the potential barrier has been reduced. Using ambipolar transport we then solve for the excess minority carrier concentrations

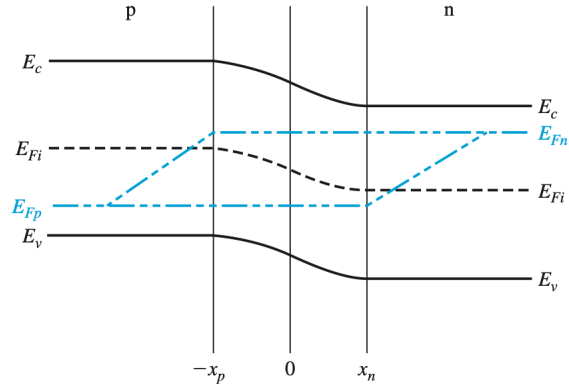
$$\delta p_n(x) = p_n(x) - p_{n0} = p_{n0} \left[ \exp \left( \frac{eV_a}{kT} \right) - 1 \right] \exp \left( \frac{x_n - x}{L_p} \right)$$

$$\delta n_p(x) = n_p(x) - n_{p0} = n_{p0} \left[ \exp \left( \frac{eV_a}{kT} \right) - 1 \right] \exp \left( \frac{x_p + x}{L_n} \right)$$

where  $L_p = \sqrt{D_p \tau_{p0}}$



**Figure 8.5** | Steady-state minority carrier concentrations in a pn junction under forward bias.



**Figure 8.6** | Quasi-Fermi levels through a forward-biased pn junction.

Using these quasi fermi levels

$$np = n_i^2 \exp \left( \frac{E_{Fn} - E_{Fp}}{kT} \right)$$

## 9.1 Ideal PN Junction Current

We find the current at the edge of the space charge region

$$J_p(x_n) = \frac{eD_p p_{n0}}{L_p} \left[ \exp \left( \frac{eV_a}{kT} \right) - 1 \right]$$

$$J_n(-x_p) = \frac{eD_n n_{p0}}{L_n} \left[ \exp \left( \frac{eV_a}{kT} \right) - 1 \right]$$

Combining these

$$J = \left[ \frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n} \right] \left[ \exp \left( \frac{eV_a}{kT} \right) - 1 \right]$$

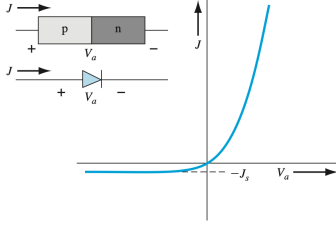


Figure 8.8 | Ideal  $I$ - $V$  characteristic of a pn junction diode.

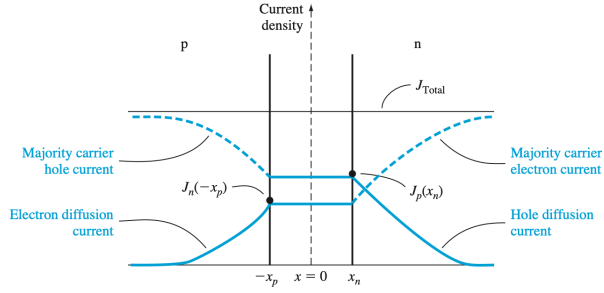


Figure 8.10 | Ideal electron and hole current components through a pn junction under forward bias.

and we define the parameter  $J_s$ , the ideal reverse bias current, to be

$$J_s = \left[ \frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n} \right]$$

We can then write the current as

$$J = J_s \left[ \exp \left( \frac{eV_a}{kT} \right) - 1 \right]$$

## 9.2 Short Diode

$$J_n(x) = \frac{eD_n n_{p0}}{W_p} \left[ \exp \left( \frac{eV_a}{kT} \right) - 1 \right]$$

Implies there is no recombination in short region. Minority carrier electron distribution changes linearly with distance.

## 9.3 Generation Recombination Currents

$$R = \frac{C_p C_n N_t (np - n_i^2)}{C_n (n + n') + C_p (p + p')}$$

This gives us a new current from the traps

$$J_{gen} = \int_0^W eG dx = \frac{en_i W}{2\tau_0}$$

where  $\tau_0 = \frac{\tau_{p0} + \tau_{n0}}{2}$ . This leads to a new reverse saturation current

$$J_R = J_s + J_{gen}.$$

Now in forward bias we have a recombination current

$$J_{rec} = \int_0^W eR dx = \frac{eW n_i}{2\tau_0} \exp \left( \frac{eV_a}{2kT} \right)$$

and the total current is

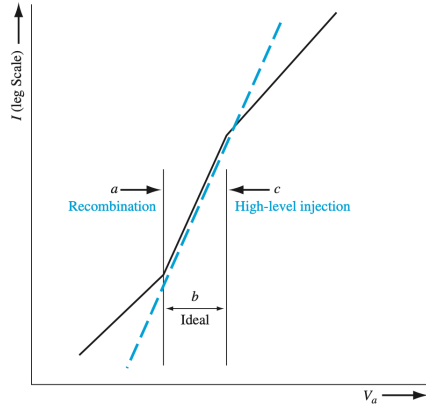
$$J = J_{rec} + J_D$$

$$J_D = J_s \exp \left( \frac{eV_a}{kT} \right)$$

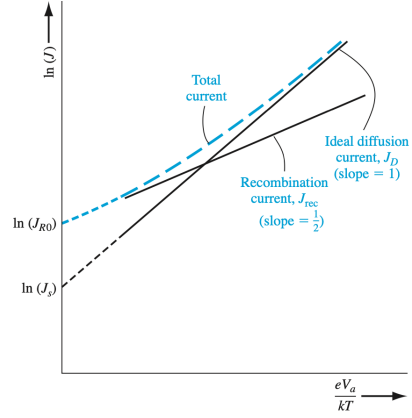
The general formula for current in a diode is given by

$$I = I_s \left[ \exp \left( \frac{eV_a}{nKT} \right) - 1 \right]$$

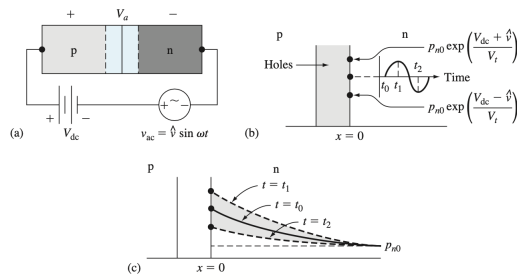
where  $n$  is 1 in a high forward bias and 2 in low forward bias.



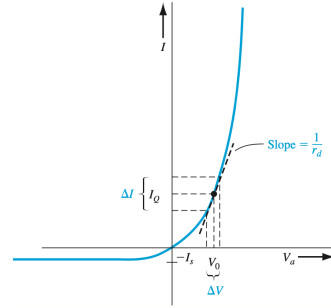
**Figure 8.17** | Forward-bias current versus voltage from low forward bias to high forward bias.



**Figure 8.16** | Ideal diffusion, recombination, and total current in a forward-biased pn junction.



**Figure 8.19** | (a) A pn junction with an ac voltage superimposed on a forward-biased dc value; (b) the hole concentration versus time at the space charge edge; (c) the hole concentration versus distance in the n region at three different times.



**Figure 8.18** | Curve showing the concept of the small-signal diffusion resistance.

## 9.4 Small Signal Model

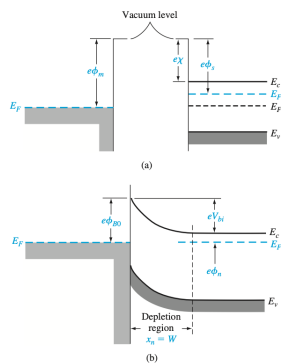
We now consider the AC characteristics of our diode. We can find the capacitance and resistance characteristics of our diode given by

$$r_d = \frac{V_t}{I_{DQ}} = \frac{V_t}{I_{p0} + I_{n0}}$$

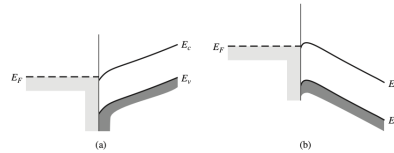
$$C_d = \frac{1}{2V_t} (I_{p0}\tau_{p0} + I_{n0}\tau_{n0})$$

creating an equivalent circuit of a resistor and capacitor in parallel.

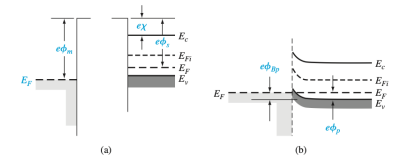
## 10 Metal-Semiconductor



**Figure 9.1** | (a) Energy-band diagram of a metal and semiconductor before contact; (b) ideal energy-band diagram of a metal-n-semiconductor junction for  $\phi_m > \phi_s$ .



**Figure 9.12** | Ideal energy-band diagram of a metal-n-type semiconductor ohmic contact (a) with a positive voltage applied to the metal and (b) with a positive voltage applied to the semiconductor.



**Figure 9.13** | Ideal energy-band diagram (a) before contact and (b) after contact for a metal-p-type semiconductor junction for  $\phi_m < \phi_s$ .

$$W = x_n = \left[ \frac{2\epsilon_s (V_{bi} + V_R)}{eN_d} \right]$$

$$C' = \left[ \frac{e\epsilon_s N_d}{2(V_{bi} + V_R)} \right]^{1/2}$$

$$J = A^* T^2 \exp\left(\frac{-e\Phi_{Bn}}{kT}\right) \left[ \exp\left(\frac{eV_a}{kT}\right) - 1 \right] = J_{sT} \left[ \exp\left(\frac{eV_a}{kT}\right) - 1 \right]$$

$$A^* = \frac{4\pi e m_n^* k^2}{h^3}$$

$$R_{\text{contact}} = \frac{\left(\frac{kT}{e}\right) \exp\left(\frac{e\Phi_{Bn}}{kT}\right)}{A^* T^2}$$

## 11 Important Tables

**Table 1.1** | A portion of the periodic table

III	IV	V
5 <b>B</b> Boron	6 <b>C</b> Carbon	
13 <b>Al</b> Aluminum	14 <b>Si</b> Silicon	15 <b>P</b> Phosphorus
31 <b>Ga</b> Gallium	32 <b>Ge</b> Germanium	33 <b>As</b> Arsenic
49 <b>In</b> Indium		51 <b>Sb</b> Antimony

**Table 1.2** | A list of some semiconductor materials

Elemental semiconductors	
Si	Silicon
Ge	Germanium
Compound semiconductors	
AlP	Aluminum phosphide
AlAs	Aluminum arsenide
GaP	Gallium phosphide
GaAs	Gallium arsenide
InP	Indium phosphide

**Table B.4** | Silicon, gallium arsenide, and germanium properties ( $T = 300$  K)

Property	Si	GaAs	Ge
Atoms ( $\text{cm}^{-3}$ )	$5.0 \times 10^{22}$	$4.42 \times 10^{22}$	$4.42 \times 10^{22}$
Atomic weight	28.09	144.63	72.60
Crystal structure	Diamond	Zincblende	Diamond
Density ( $\text{g/cm}^3$ )	2.33	5.32	5.33
Lattice constant ( $\text{\AA}$ )	5.43	5.65	5.65
Melting point ( $^{\circ}\text{C}$ )	1415	1238	937
Dielectric constant	11.7	13.1	16.0
Bandgap energy (eV)	1.12	1.42	0.66
Electron affinity, $\chi$ (V)	4.01	4.07	4.13
Effective density of states in conduction band, $N_c$ ( $\text{cm}^{-3}$ )	$2.8 \times 10^{19}$	$4.7 \times 10^{17}$	$1.04 \times 10^{19}$
Effective density of states in valence band, $N_v$ ( $\text{cm}^{-3}$ )	$1.04 \times 10^{19}$	$7.0 \times 10^{18}$	$6.0 \times 10^{18}$
Intrinsic carrier concentration ( $\text{cm}^{-3}$ )	$1.5 \times 10^{10}$	$1.8 \times 10^6$	$2.4 \times 10^{13}$
Mobility ( $\text{cm}^2/\text{V}\cdot\text{s}$ )			
Electron, $\mu_n$	1350	8500	3900
Hole, $\mu_p$	480	400	1900
Effective mass ( $\frac{m^*}{m_0}$ )			
Electrons	$m_l^* = 0.98$	0.067	1.64
	$m_t^* = 0.19$		0.082
Holes	$m_{lh}^* = 0.16$	0.082	0.044
	$m_{hh}^* = 0.49$	0.45	0.28
Density of states effective mass			
Electrons ( $\frac{m_{dn}^*}{m_0}$ )	1.08	0.067	0.55
Holes ( $\frac{m_{dp}^*}{m_0}$ )	0.56	0.48	0.37
Conductivity effective mass			
Electrons ( $\frac{m_{cn}^*}{m_0}$ )	0.26	0.067	0.12
Holes ( $\frac{m_{cp}^*}{m_0}$ )	0.37	0.34	0.21

**Table 8.1** | Commonly used terms and notation for this chapter

Term	Meaning
$N_a$	Acceptor concentration in the p region of the pn junction
$N_d$	Donor concentration in the n region of the pn junction
$n_{n0} = N_d$	Thermal-equilibrium majority carrier electron concentration in the n region
$p_{p0} = N_a$	Thermal-equilibrium majority carrier hole concentration in the p region
$n_{p0} = n_i^2/N_a$	Thermal-equilibrium minority carrier electron concentration in the p region
$p_{n0} = n_i^2/N_d$	Thermal-equilibrium minority carrier hole concentration in the n region
$n_p$	Total minority carrier electron concentration in the p region
$p_n$	Total minority carrier hole concentration in the n region
$n_p(-x_p)$	Minority carrier electron concentration in the p region at the space charge edge
$p_n(x_n)$	Minority carrier hole concentration in the n region at the space charge edge
$\delta n_p = n_p - n_{p0}$	Excess minority carrier electron concentration in the p region
$\delta p_n = p_n - p_{n0}$	Excess minority carrier hole concentration in the n region

### 11.1 Constants

Avogadro's number

$$N_A = 6.02 \times 10^{+23} \text{ atoms per gram molecular weight}$$

Boltzmann's constant

$$k = 1.38 \times 10^{-23} \text{ J/K} \\ = 8.62 \times 10^{-5} \text{ eV/K}$$

Electronic charge (magnitude)

$$e = 1.60 \times 10^{-19} \text{ C}$$

Free electron rest mass

$$m_0 = 9.11 \times 10^{-31} \text{ kg}$$

Permeability of free space

$$\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$$

Permittivity of free space

$$\epsilon_0 = 8.85 \times 10^{-14} \text{ F/cm} \\ = 8.85 \times 10^{-12} \text{ F/m}$$

Planck's constant

$$h = 6.625 \times 10^{-34} \text{ J-s} \\ = 4.135 \times 10^{-15} \text{ eV-s}$$

$$\frac{h}{2\pi} = \hbar = 1.054 \times 10^{-34} \text{ J-s}$$

Proton rest mass

$$M = 1.67 \times 10^{-27} \text{ kg}$$

Speed of light in vacuum

$$c = 2.998 \times 10^{10} \text{ cm/s}$$

Thermal voltage ( $T = 300 \text{ K}$ )

$$V_t = \frac{kT}{e} = 0.0259 \text{ V}$$

$$kT = 0.0259 \text{ eV}$$