ECE 2 Cheatsheet

# 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.

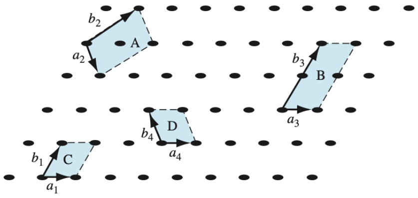


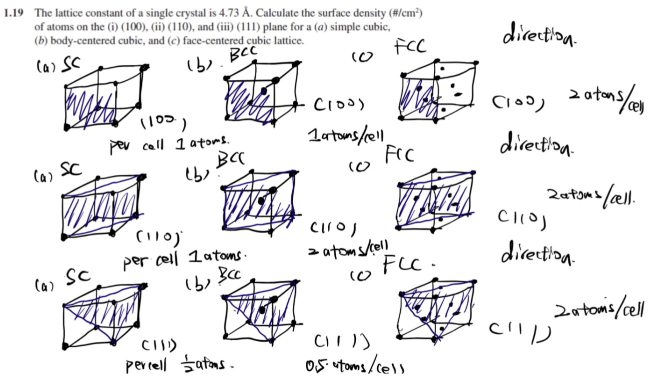
**Figure 1.3** | Two-dimensional representation of a single-crystal lattice showing various possible unit cells.

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

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



**1.19** The lattice constant of a single crystal is 4.73 Å. Calculate the surface density (#/cm²) of atoms on the (i) (100), (ii) (110), and (iii) (111) plane for a (*a*) simple cubic, (*b*) body-centered cubic, and (*c*) face-centered cubic lattice.

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

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

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

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

$\Psi(x)$ and $\partial\Psi(x)/\partial x$ must be finite, single-valued, and continous. 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.

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

### 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 $V_0$.

$$\Psi_1(x)=A_1e^{jkx}+B_2e^{-jkx}$$

$$\Psi_2(x)=A_2e^{-k_2x}+B_2e^{k_2x}$$

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

$$\Psi_2(x)=A_2e^{-k_2x}$$

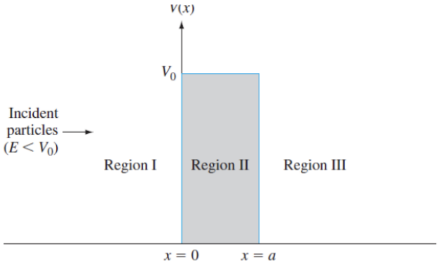
We also find that

$$B_1 = \frac{-k_2 + 2jk_1k_2 - k_1^2}{k_2^2 + k_1^2} \cdot A_1$$
$$A_2 = \frac{2k_1(k_1 - jk_2)}{k_2^2 + k_1^2} \cdot A_2$$

The reflection coeffient is also found

$$R = \frac{B_1B_1^*}{A_1A_1^*} = \frac{(k_2^2 - k_1^2) + 4k_1^2k_2^2}{(k_2^2 + k_1^2)^2}$$

### 2.3.4 Potential Barrier



3 solutions for region I, II, and III.

$$\Psi_1(x) = A_1e^{jk_1x} + B_1e^{-jk_1x}$$
$$\Psi_2(x) = A_2e^{k_2x} + B_2e^{-k_2x}$$
$$\Psi_3(x) = A_3e^{jk_1x} + B_3e^{-jk_1x}$$

where

$$k_1 = \sqrt{\frac{2mE}{\hbar^2}}$$
$$k_2 = \sqrt{\frac{2m}{\hbar^2}(V_0 - E)}$$

Transmission is given by

$$T \approx 16\frac{E}{V_0}(1 - \frac{E}{V_0})e^{-2k_2a}$$

## 2.4 Energy of electron (Hydrogen Model)

$$E_n = \frac{-m_0e^4}{(4\pi\epsilon_0)^2 2\hbar^2n^2}$$

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

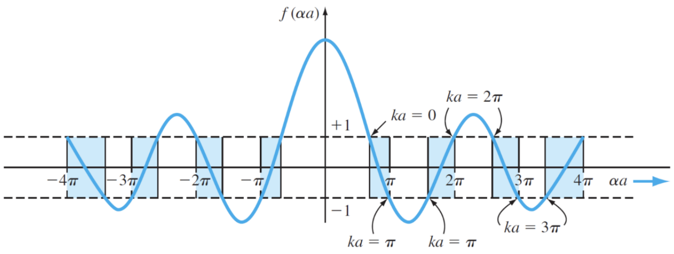
# 3 Quantum Theory of Solids

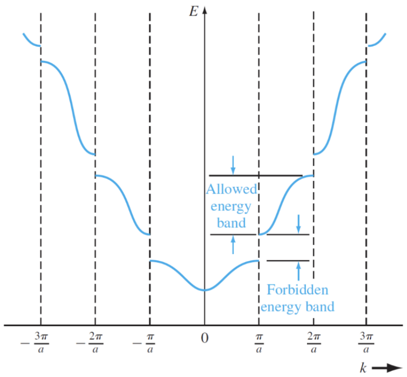
## 3.1 Kronig Penney Model

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

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

$$F_{ext} = m^* a$$
$$\frac{1}{\hbar^2}\frac{d^2E}{dk^2} = \frac{1}{m^*}$$
$$a = \frac{-eE}{m_n^*}$$

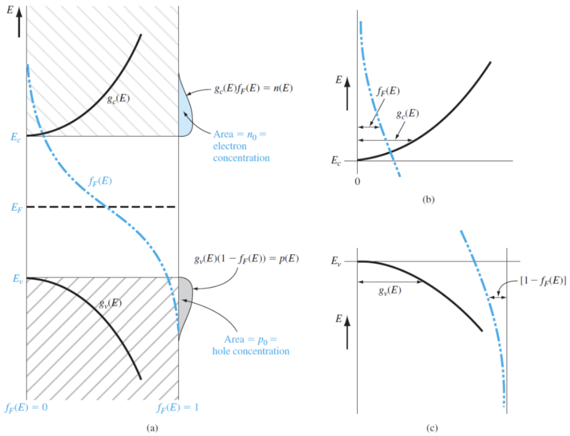
## 3.4 Probabiltiy and Density Distribution

The Fermi-Dirac distribution is given by

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

Maxwell-Boltzmann Approximation

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



# 4 Semiconductors in Equilibirum

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

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

The equilibrium concentration of electrons in CB is

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

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

Holes:

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

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

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

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

## 4.1 Intrinsic Carrier Concentration

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

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

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

$$\boxed{n_o p_o = n_i^2}$$

The fermi level is given by

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

## 4.2 Extrinsic Semiconductor

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

$$n_0 = n_i \exp[\frac{E_F - E_{Fi}}{kT}]$$

$$p_0 = n_i \exp[\frac{-(E_F - E_{Fi})}{kT}]$$

### 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 concetration 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.

$$n_0 + N_a^- = p_0 + N_d^+$$
$$n_0 + (N_a - p_a) = p_o + (N_d - n_d)$$

If we assume complete ionization

$$n_0 + N_a = p_0 + N_d$$

The electron concentration can then be determined by

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

Similarly the holes concentration is

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

### 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

$$E_c - E_F = kT \ln \frac{N_c}{N_d - N_a}$$
$$E_F - EFi = kT \ln \frac{n_0}{n_i}$$

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

$$E_F - E_v = kT \ln \frac{N_v}{p_o}$$
$$E_F - E_v = kt \ln \frac{N_v}{N_a}$$
$$E_{Fi} - E_F = kT \ln \frac{p_0}{n_i}$$

# 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 conduvivitiy 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

$$n = n_0 + \delta n$$
$$p = p_0 + \delta p$$

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

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

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

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

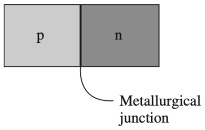
## 7.3 Quasi Fermi Level

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

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

# 8 PN Junction

## 8.1 Basic Structure



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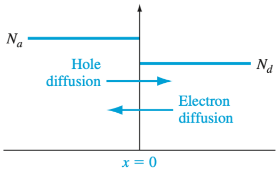

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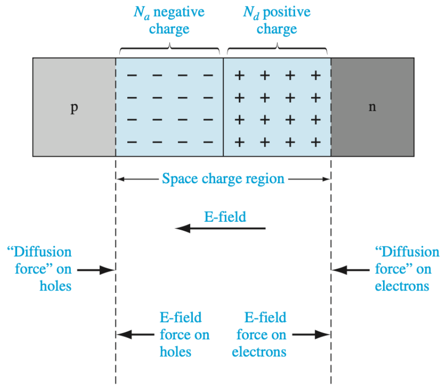


## 8.2 Zero Bias

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

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

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

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

## 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

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

and

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

$$E_{max} = \frac{-2(V_{bi} + V_R)}{W}.$$

## 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

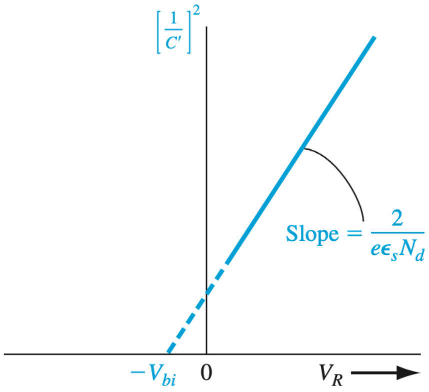


**Figure 7.11** | $(1/C')^2$ versus $V_R$ of a uniformly doped pn junction.

## 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 Nonuniformally Doped Junctions

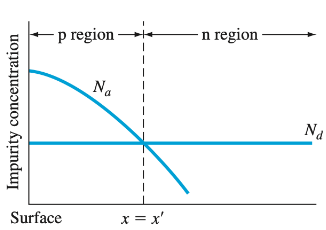


**Figure 7.16** | Impurity concentrations of a pn junction with a nonuniformly doped p region.

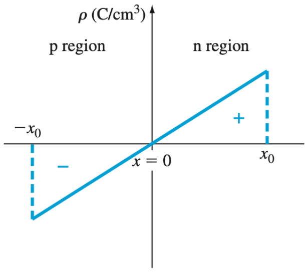


**Figure 7.17** | Space charge density in a linearly graded pn junction.

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

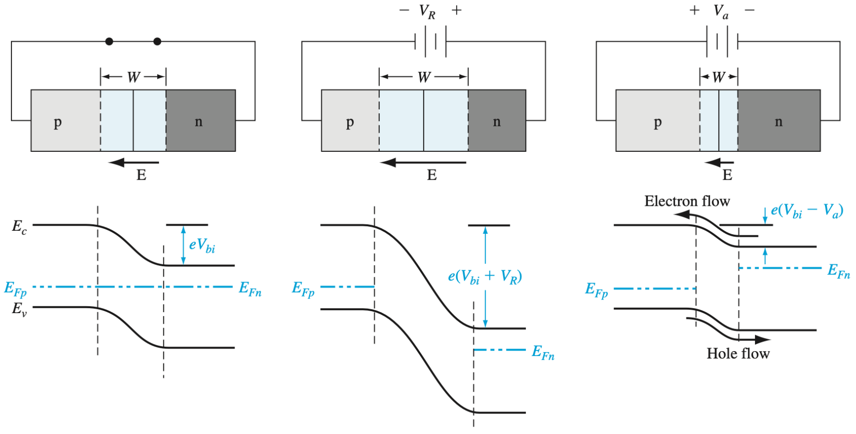
$$x_0 = \left[\frac{3}{2}\frac{\epsilon_s}{ea}(V_{bi} + V_R)\right]^{1/3}$$

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

Where a is the gradient of net impurity concentration.

# 9 PN Junction Diode

Now we examine diodes in both forward and reverse bias.



(a) (b) (c)

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

$$n_{p0} = n_{n0}\exp\left(\frac{-eV_{bi}}{kT}\right)$$

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

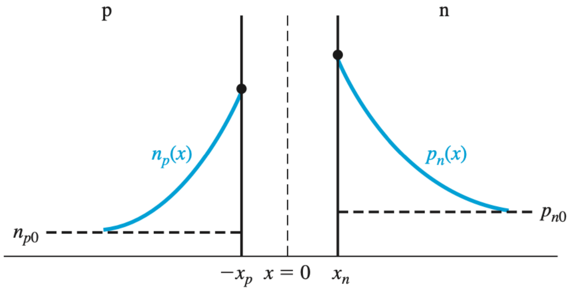


**Figure 8.5** | Steady-state minority carrier concentrations in a pn junction under forward bias.

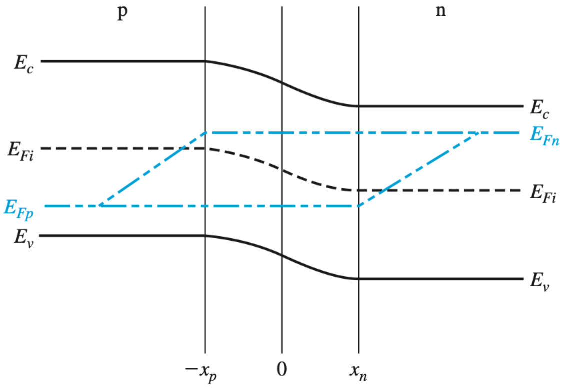


**Figure 8.6** | Quasi-Fermi levels through a forward-biased pn junction.

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

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

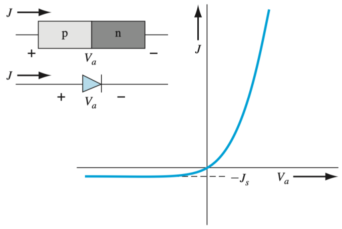


**Figure 8.8** | Ideal *I–V* characteristic of a pn junction diode.

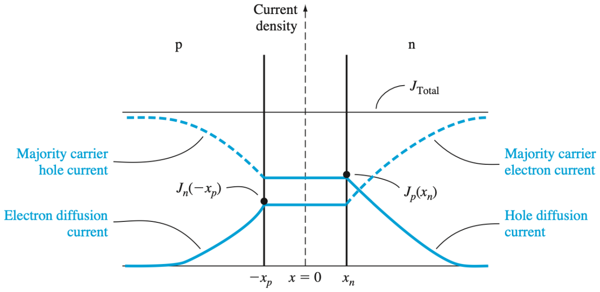


**Figure 8.10** | Ideal electron and hole current components through a pn junction under forward bias.

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

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

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

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

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

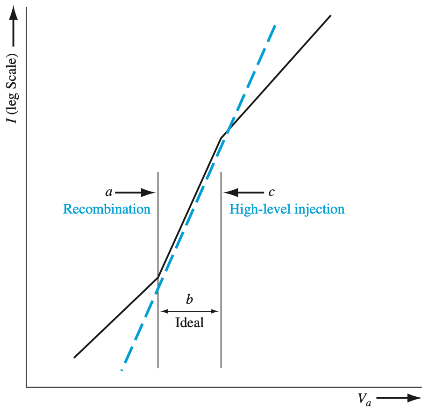


**Figure 8.17** | Forward-bias current versus voltage from low forward bias to high forward bias.

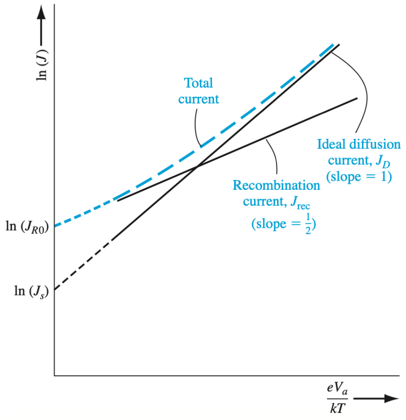


**Figure 8.16** | Ideal diffusion, recombination, and total current in a forward-biased pn junction.

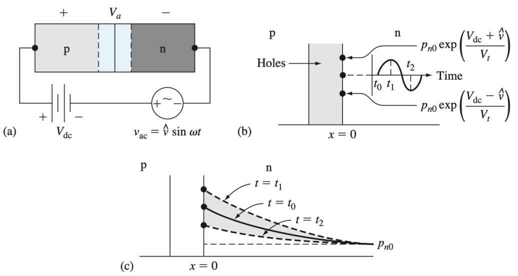


**Figure 8.19** | (a) A pn junction with an ac voltage superimposed on a forward-biased dc value; (b) the hole concentration versus time at the space charge edge; (c) the hole concentration versus distance in the n region at three different times.

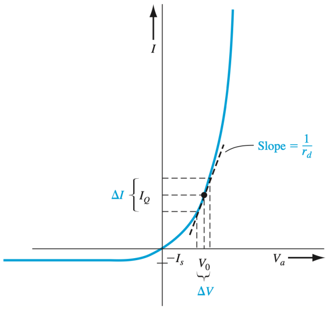


**Figure 8.18** | Curve showing the concept of the small-signal diffusion resistance.

## 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

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

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

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

# 10 Metal-Semiconductor

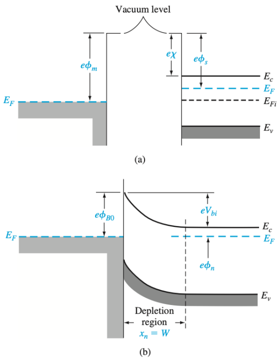


**Figure 9.1** | (a) Energy-band diagram of a metal and semiconductor before contact; (b) ideal energy-band diagram of a metal–n-semiconductor junction for $\phi_m > \phi_s$.

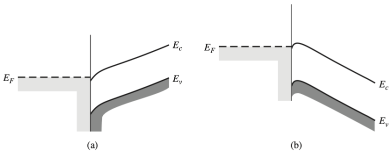


**Figure 9.12** | Ideal energy-band diagram of a metal-n-type semiconductor ohmic contact (a) with a positive voltage applied to the metal and (b) with a positive voltage applied to the semiconductor.

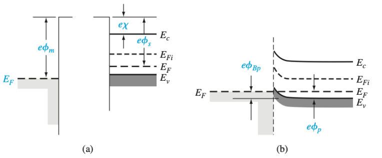


**Figure 9.13** | Ideal energy-band diagram (a) before contact and (b) after contact for a metal–p-type semiconductor junction for $\phi_m < \phi_s$.

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

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

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

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

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

# 11 Important Tables

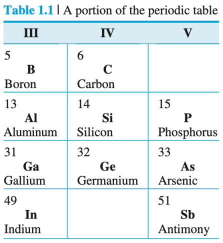


**Table 1.1** | A portion of the periodic table

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

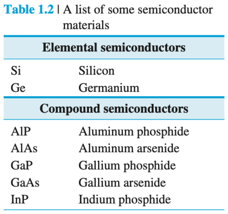


**Table 1.2** | A list of some semiconductor materials

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

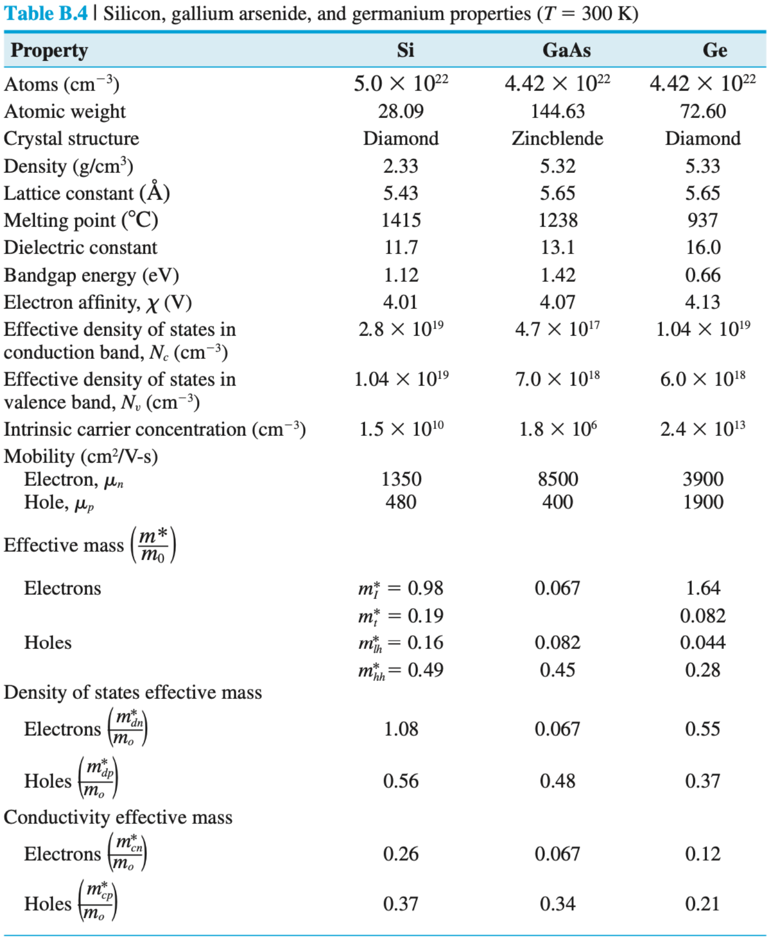


**Table B.4** | Silicon, gallium arsenide, and germanium properties ($T$ = 300 K)

| 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 (Å) | 5.43 | 5.65 | 5.65 |
| Melting point (°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 ($\text{cm}^2$/V-s) | | | |
| Electron, $\mu_n$ | 1350 | 8500 | 3900 |
| Hole, $\mu_p$ | 480 | 400 | 1900 |
| Effective mass $\left(\frac{m^*}{m_0}\right)$ | | | |
| 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 $\left(\frac{m_{dn}^*}{m_o}\right)$ | 1.08 | 0.067 | 0.55 |
| Holes $\left(\frac{m_{dp}^*}{m_o}\right)$ | 0.56 | 0.48 | 0.37 |
| Conductivity effective mass | | | |
| Electrons $\left(\frac{m_{cn}^*}{m_o}\right)$ | 0.26 | 0.067 | 0.12 |
| Holes $\left(\frac{m_{cp}^*}{m_o}\right)$ | 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 | $N_A = 6.02 \times 10^{+23}$ atoms per gram molecular weight |
| Boltzmann's constant | $k = 1.38 \times 10^{-23}$ J/K<br>$= 8.62 \times 10^{-5}$ eV/K |
| Electronic charge (magnitude) | $e = 1.60 \times 10^{-19}$ C |
| Free electron rest mass | $m_0 = 9.11 \times 10^{-31}$ kg |
| Permeability of free space | $\mu_0 = 4\pi \times 10^{-7}$ H/m |
| Permittivity of free space | $\epsilon_0 = 8.85 \times 10^{-14}$ F/cm<br>$= 8.85 \times 10^{-12}$ F/m |
| Planck's constant | $h = 6.625 \times 10^{-34}$ J-s<br>$= 4.135 \times 10^{-15}$ eV-s<br>$\frac{h}{2\pi} = \hbar = 1.054 \times 10^{-34}$ J-s |
| Proton rest mass | $M = 1.67 \times 10^{-27}$ kg |
| Speed of light in vacuum | $c = 2.998 \times 10^{10}$ cm/s |
| Thermal voltage ($T = 300$ K) | $V_t = \frac{kT}{e} = 0.0259$ V<br>$kT = 0.0259$ eV |