

→ The crystal structure of Solids

P:

Resistivity
(intr)

L:
length

A:
Area

Visible
light:
Photons
 $E = 1.5-3 \text{ eV}$

Trapped
Energy
in Solid

- Electrical properties of Material

$$\text{Resistance: } R = \rho \frac{L}{A}$$

$$\text{Conductivity: } \sigma = \frac{1}{R}$$

Metal \rightarrow good R

Dielectrics \rightarrow good σ

Semiconductor \rightarrow R and σ be controlled

- Semiconductor

Conduction band

Valence band

bandgap \rightarrow forbidden energy region

\hookrightarrow Semiconductors

bandgap energy $< 3 \text{ eV}$

- Silicon

Silicon: atom # = 14

$e^- \# = 14$
proton # = 14

- Quantum numbers

electron configuration of silicon

$n \ I \ m_1 \text{ or } m_2$

(bigger, E) m : the floor that electron on

(orbital) l : shape of the room (sphere ($l=0$), dumbbell ($l=1$))

(l to l) $-m_l$: which direction the room is facing.

m_s : electron's spin

$1s^2$: first floor, spherical room, 2 electrons

- Valence electrons

$1s^2 2s^2 2p^6 3s^2 3p^2$

\hookrightarrow Valence electrons: 3 \rightarrow 4

covalent bond: $\text{O}=\text{O}$

Silicon

in a solid
orderly
the atoms
arranged

o Crystallinity

In a single crystal semiconductor, the atoms are arrayed with perfect periodicity, in a lattice

high Crystallinity \rightarrow more order

lattice
Unit or
primitive
cell is
reported

In polycrystalline material : many grains (arrayment)

primitive cell : smallest unit cell

= volume of the solid crystal

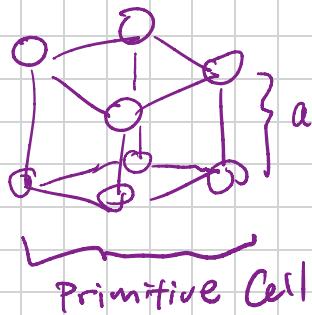
o Bravais Lattice (3D)

$$\vec{r} = p\vec{a} + q\vec{b} + s\vec{c}$$

lattice vector

• unique BN lattice

o Simple Cubic Structure



a (lattice constant)

$$\vec{r} = p\vec{a} + q\vec{b} + s\vec{c}$$

$$\text{unit cell} \rightarrow \frac{1}{8} \times 1 \text{ atom} \quad \left. \begin{matrix} \\ \end{matrix} \right\} \frac{1}{8} \times \frac{1}{8} = 1 \text{ atom}$$

sharing atoms



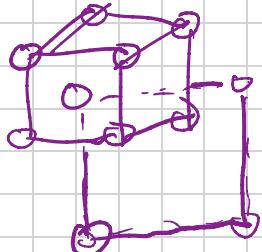
$$A = \frac{\pi r^2}{\partial} n M$$

volume density: # of atoms
in a certain volume of crystal

$$= \frac{1}{a^3}$$

normally $a = 0.5 \text{ nm}$

o Body-Centred Cubic (BCC) structure



$$\vec{r} = \frac{1}{2}\vec{a} + \frac{1}{2}\vec{b} + \frac{1}{2}\vec{c}$$

$$\left. \begin{matrix} 8 \times \frac{1}{8} \\ 1 \text{ in center} \end{matrix} \right\} 2 \text{ atoms}$$

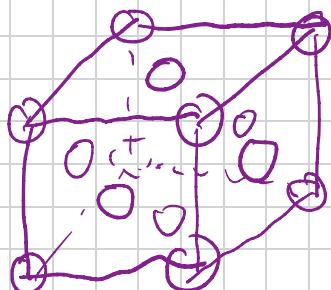
o Coordination number

How efficiently atoms fill in the space in a crystal

$$\hookrightarrow \text{Packing factor} = \frac{(\# \text{ of atoms}/\text{cell}) (\text{volume of each atom})}{\text{volume of unit cell}}$$

o Face-Centred cubic (FCC)

2 Unit Cell shared on atom



$$8 \times \frac{1}{8} \left. \right\} 1 + 3 = 4 \\ 6 \times \frac{1}{2}$$

o Miller indices

A way of identifying crystal plane

$$\vec{r} = p\hat{a} + q\hat{b} + r\hat{c} \rightarrow \text{on Wafer}$$

$$3 \quad 2 \quad 1 \rightarrow \left(\frac{1}{3}, \frac{1}{2}, \frac{1}{1} \right) \rightarrow \text{Multiple 6}$$

reciprocal

(236) plane $\longleftrightarrow (2, 3, 6)$

Any plane parallel to this hence same Miller indices

Family $\{100\} = (100) (010) (001)$

o Crystal direction

describe the direction that a vector points inside the crystal

$[111] \quad [100] \dots$

o Crystal structure of silicon

Simple cubic 6 BCC 8 FCC 12

- Diamond Crystal Structure \rightarrow FCC
 - ↳ neighboring slices align
- Zincblende structure -
 - ↳ two type atoms

→ Quantum mechanics

describe particles behavior, deals with potential (probabilities)

E : energy
eV

$h = 6.626 \times 10^{-34}$

V : freq
(Hz)

- Photoelectric effect:

$$\text{Photo Energy : } E = hV$$

$$\text{Kinetic energy : excess energy } T: hV - \frac{\Phi}{eV}$$

- The two slit experiment

light behave { wave: how they move through space
particle: how they interact with other particles

- Blackbody radiation

Temperature { $\uparrow \rightarrow$ shorter wavelength
 $\downarrow \rightarrow$ long wavelength

- viewing light as a particle with a quantized energy solved this

$$\text{How much energy is emitted at each wavelength} \quad \rho(\lambda) = \frac{2\pi hc^2}{\lambda^5} \left[\exp\left(\frac{hc}{\lambda k_B T}\right) - 1 \right]$$

ρ : spectral energy density

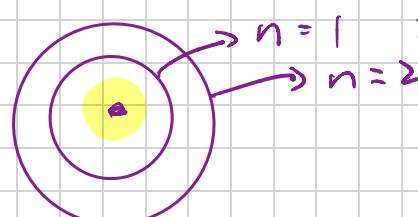
λ : wavelength

$c = 2.9979 \times 10^8 \text{ m/s}$ (speed of light)

$h = 6.626 \times 10^{-34} \text{ m}^2 \text{ kg/s}$ (Planck's constant)

$k_B = 1.381 \times 10^{-23} \text{ m}^2 \text{ kg}/(\text{s}^2 \text{ K})$ (Boltzmann constant)

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Electron energy level

$$E = h\nu = E_2 - E_1$$

High Energy level

Low Energy level

No Two
 e^- occupy
one state

- The Heisenberg uncertainty principle

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

momentum & position

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

Energy & time

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

The Schrödinger equation

$$i\hbar \frac{\partial}{\partial t} \Psi = \hat{H} \Psi$$

Ψ : Wavefunction

\hat{H} : $\hat{T} + \hat{V}$

How energy of system
influence its wavefunction

kinetic E

Potential E

momentum operator in QM: $\hat{p} = i\hbar \frac{\partial}{\partial x}$

$$\therefore \hat{T} = -\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2}$$

wavefunction: electron is described by wavefunction,
describe quantum state of particle in space and time

$\int |\Psi|^2 = 1$
find ϵ
at some place

$$\int_a^b |\Psi(x,t)|^2 dx \quad \text{probability location, likely find e at specific position}$$

$$|\Psi(x,t)|^2 = \Psi(x,t) \cdot \Psi^*(x,t)$$

Energy that correspond to Wavefunction \rightarrow Solution of Schrödinger equation

Separation of variables

wavefunction $\left\{ \begin{array}{l} \text{time-dependent Component } \textcircled{1} \\ \text{space-dependent Component } \textcircled{2} \end{array} \right.$

$$i\hbar \cdot \frac{1}{\phi(t)} \cdot \frac{\partial \phi(t)}{\partial t} = \eta$$

$$\text{solution } \phi(t) = e^{i\eta/\hbar t}$$



$$\phi(t) = e^{i(E/\hbar)t}$$

$$= e^{-iEt/\hbar}$$

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

Time-independent Schrödinger equation

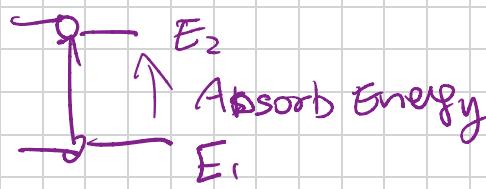
usually solve this for potential function

• PDF \rightarrow Find particle somewhere $\rightarrow \psi(x)$

$$\int_{-\infty}^{\infty} |\psi(x)|^2 dx = 1$$

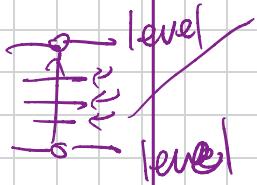
Week 3

→ Energy level Splitting



↑
1st
State
ground State

Energy band formation :



many atoms come together, individual atomic energy split and form

$$\overline{E} - E_{n1} = \frac{\Delta E}{N} = \frac{1\text{ eV}}{10^{22}} = 10^{-22}\text{ eV}$$

$\overbrace{\quad}^J$

energy band width # atoms

while energy levels are discrete, they closely space
think of Continuum of energy level

- Bloch's theorem (in periodic potential, wavefunction can be:

$$\psi(x) = U(x) e^{i k x}$$

$\overbrace{\quad}^U$ traveling wave

\hookrightarrow periodic function

full wavefunction: $\psi(x,t) = U(x) e^{i(kx - (E/\hbar)t)}$

- Kronig - Penney model: e^- behave in periodic Potential

Transcendental equation:

$$P \frac{\sin 2a}{2a} + \cos 2a = \cos ka$$

— Can't be solved

$$P = \frac{m V_0 b a}{\hbar^2}$$

Conventional Way

Graphic Way

Numerical approach

o Effective mass

electric field is applied to semiconductor, e^- in conduction band move in response to the field

$$\text{Total force: } F_{\text{total}} = F_{\text{ext}} + F_{\text{in}} = ma$$

m^* → parameter: modify how e^- respond external force

$$F_{\text{ext}} = m^* \cdot a$$

$$E = \frac{p^2}{2m^*} = \frac{k^2 k^2}{2m^*} \rightarrow \text{effective mass of Semiconductor}$$

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

Greater Curvature

↪ Small m^*

o Energy band

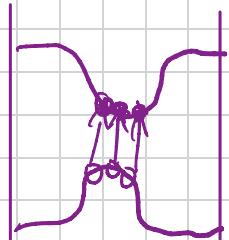
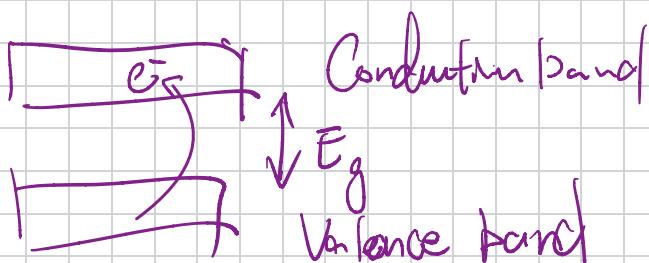
indirect bandgap: silicon

valence band max
conduction band min

direct bandgap: GaAs

good for light emittor

o Electrical Conduction



Current density → # of e^-

$$J = q \sum_{i=1}^N v_i$$

charge → velocity

$$\text{Velocity: } V(E) = \frac{e k}{m^*}$$

$$\sum F = qE = ma$$

\uparrow
total
force of e^-



- Electric field applied

- hole

hole expressed by current density:

$$J = +e \sum v_i$$

v_i → velocity



- Material

An insulator has electronic bands that are either completely empty or completely full

- When an electric field is applied, no current flows
- In a filled band, electrons cannot move to other states (they are all full), so no momentum asymmetry can be achieved

- Semiconductor:

most e^- in valence band

- metal

- They can either have:
 - A partially-filled band - many electrons for conduction; or
 - Overlap between the valence and conduction bands



o week 4

→ Density of states

Describe the number of available energy states per unit volume at each energy in a material.

Energy State : a specific energy level that an electron can occupy.



(DOS depend on electronic properties (crystal structure))

$$g(E) = 0, \quad E_v < E < E_c \quad \text{no states in forbidden energy region}$$

\downarrow \downarrow
Top of valence band bottom of conduction band

DOS

$$\tilde{g}_v(E) = \frac{4\pi(2m^*_p)^{3/2}}{h^3} \sqrt{E_v - E} \quad E \leq E_v$$

$$\tilde{g}_c(E) = \frac{4\pi(2m^*_n)^{3/2}}{h^3} \sqrt{E - E_c} \quad E \geq E_c$$

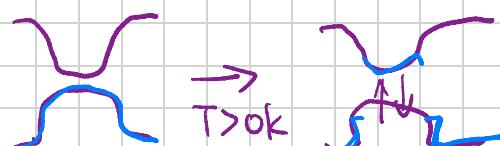
→ Fermi Energy :

Energy level finding an e^- by 50% chance at $T=0K$

$$N_0 = \int_0^{E_F} g(E) dE$$

At $T=0K$, all electronic states with energies below E_F are filled

For a semi, can expect Fermi energy is located somewhere in forbidden energy region.



- Thermal equilibrium remain Constant

\uparrow up \downarrow down at same time

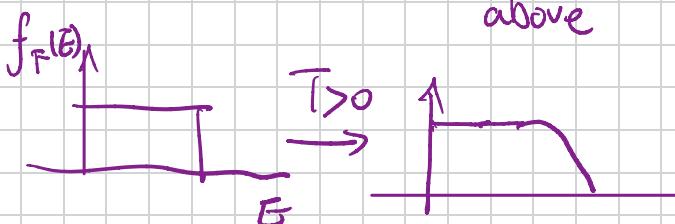
- The Fermi-Dirac Probability function: probability describes behavior of electron in semi

P% that an Energy level is occupied by an e^- at T distribution.

$$\frac{N(E)}{g(E)} = f_F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{k_B T}\right)}$$

$N(E)$:	# of particles/J/cm ³
$g(E)$:	# of states/J/cm ³
$f_F(E)$:	Fermi-Dirac distribution
E_F :	Fermi energy
T :	Temperature (K)
k_B :	1.38×10^{-23} J/K

$T = 0\text{ K}$, All energy below Fermi energy are filled above empty



At $T > 0$, 50% chance that energy state at E_F will be occupied

$$f_F(E = E_F) = \frac{1}{\exp\left(\frac{E_F - E}{k_B T}\right)} = \frac{1}{2}$$

- Maxwell Approximation

If energy levels $>$ Fermi energy, then

$$E - E_F \gg k_B T$$

$$f_F(E) \approx \exp\left(\frac{-(E - E_F)}{k_B T}\right)$$

→ Semiconductor in equilibrium

$$e^- : \frac{n(E)}{n(E)} = \frac{\rho_c(E)}{\rho_c(E)} f_F(E)$$

density of e^- state state occupied

$$\text{hole} ; p(E) = g_v(E)[1 - f_F(E)]$$

at forbidden energy region: $n(E) = p(E) = 0$

For undoped semi: $n_0 = p_0$

AT Room
 $T : k_B T =$
 0.026eV

n_0 :
area under
 $n(E) \rightarrow$
electrons in
conduction
band

p_0 :
 \sim

→ Fermi energy: highest energy level e^- occupy at $T = 0\text{K}$, dividing line occupied/unoccupied energy states

In metal Fermi energy lies within an energy band

The Fermi energy

- Here are the DOS expressions again for reference:

$$\text{Conduction band: } g_c(E) = \frac{4\pi(2m_n^*)^{3/2}}{h^3} \sqrt{E - E_c} \quad E \geq E_c$$

(DOS)

$$\text{Valence band: } g_v(E) = \frac{4\pi(2m_p^*)^{3/2}}{h^3} \sqrt{E_v - E} \quad E \leq E_v$$

- If the effective masses of electrons and holes are the same, the DOS in the conduction band and valence band will be symmetric.

- If this is true, then we can only have $n_0 = p_0$ if the Fermi-Dirac distribution is symmetric about the mid-gap energy, where

$$E_{\text{mid-gap}} = \frac{E_c + E_v}{2}$$

- This means that $E_F = E_{\text{mid-gap}}$

Equilibrium concentration of electrons

- Next, we will write the expression for the equilibrium density of electrons in the conduction band as:

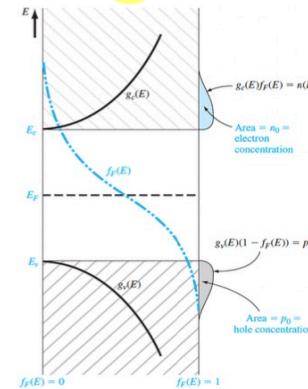
$$n_0 = \int_{E_c}^{\infty} g_c(E) f_F(E) dE$$

- For electrons in the conduction band at or near room temperature, we can normally use the Maxwell-Boltzmann approximation:

$$f_F(E) \approx \exp\left(-\frac{(E - E_F)}{k_B T}\right)$$

- So, we can write:

$$n_0 = \int_{E_c}^{\infty} \frac{4\pi(2m_n^*)^{3/2}}{h^3} \sqrt{E - E_c} \exp\left[-\frac{(E - E_F)}{k_B T}\right] dE$$



Equilibrium density of e^- in conduction band

Equilibrium concentration of electrons

- After some fancy integration (see textbook), we get the following expression:

$$n_0 = N_c \exp\left[-\frac{(E_c - E_F)}{k_B T}\right]$$

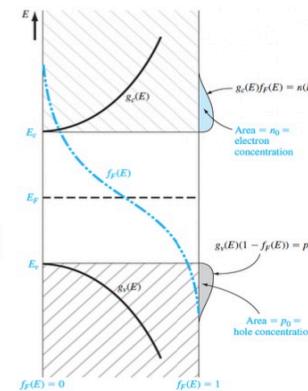
$$N_c = 2 \left(\frac{2\pi m_n^* k_B T}{h^2} \right)^{3/2}$$

Solution
effective density of states

- Here, N_c is the effective density of states function in the conduction band. We are going to use it very frequently for room temperature ($T = 300\text{ K}$) in silicon, where its value is:

$$N_c = 2.5 \times 10^{19} \text{ cm}^{-3}$$

silicon at room temperature



Equilibrium concentration of holes

- We can go through a similar procedure for holes in the valence band:

$$p_0 = \int_{-\infty}^{E_v} g_v(E) [1 - f_F(E)] dE$$

- Note that:

$$\begin{aligned} 1 - f_E(E) &= 1 - \frac{1}{1 + \exp\left(\frac{E_F - E}{k_B T}\right)} = \frac{\exp\left(\frac{E_F - E}{k_B T}\right)}{1 + \exp\left(\frac{E_F - E}{k_B T}\right)} \\ &= \frac{\exp\left(\frac{E_F - E}{k_B T}\right)}{1 + \exp\left(\frac{E_F - E}{k_B T}\right)} \cdot \frac{\exp\left(\frac{E - E_F}{k_B T}\right)}{\exp\left(\frac{E - E_F}{k_B T}\right)} = \frac{1}{1 + \exp\left(\frac{E - E_F}{k_B T}\right)} \end{aligned}$$

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Hole density
in Valence band

Equilibrium concentration of holes

- Using the Maxwell-Boltzmann approximation, we can set up the integral as follows:

$$p_0 = \int_{-\infty}^{E_v} \frac{4\pi(2m_p^*)^{3/2}}{h^3} \sqrt{E_v - E} \exp\left[-\frac{(E_F - E)}{k_B T}\right] dE$$

- This integral simplifies to: $p_0 = N_v \exp\left[-\frac{(E_F - E_v)}{k_B T}\right]$

Solution

- The effective density of states function in the valence band is defined as:

$$N_v = 2 \left(\frac{2\pi m_p^* k_B T}{h^2} \right)^{3/2} \quad \text{effective density of state}$$

- For silicon at $T = 300$ K, we will use: $N_v = 1.04 \times 10^{19} \text{ cm}^{-3}$

→ Intrinsic Carrier Concentration

In intrinsic semiconductor is single crystal,
free of impurities and dopants

- Using the equations we just examined, we can write:

$$n_i = N_c \exp\left[-\frac{(E_c - E_{Fi})}{k_B T}\right] \quad \text{Concentration of } e^- = \text{Concentration of Conduct band}$$

$$p_i = n_i = N_v \exp\left[-\frac{(E_{Fi} - E_v)}{k_B T}\right] \quad \text{hole Valence band}$$

$$n_i = p_i$$

- Here, E_{Fi} is the Fermi energy of the intrinsic semiconductor

- What happens if we multiply these together?

$$\text{Concentration of intrinsic carrier (semi)} [n_i p_i] = n_i^2 = N_c N_v \exp\left[-\frac{(E_c - E_{Fi})}{k_B T}\right] \cdot \exp\left[-\frac{(E_{Fi} - E_v)}{k_B T}\right]$$

Carrier
(semi)

$$n_i^2 = N_c N_v \exp\left[-\frac{(E_c - E_v)}{k_B T}\right] = N_c N_v \exp\left[-\frac{E_g}{k_B T}\right]$$

- For a fixed temperature, n_i is a constant

- Silicon, 300K:

- Using the equation above:

$$n_i = 6.95 \times 10^9 \text{ cm}^{-3}$$

- Experimentally measured value:

$$n_i = 1.5 \times 10^{10} \text{ cm}^{-3}$$

Theoretical
practical

Intrinsic Fermi energy

Concentration

- We can now determine the exact position of the Fermi energy level in an intrinsic semiconductor.
- The concentrations of conduction band electrons and valence band holes are equal:

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

- Solving this, we get:

$$\text{Fermi energy} \quad E_{Fi} = \frac{1}{2}(E_c + E_v) + \frac{1}{2}k_B T \ln\left(\frac{N_v}{N_c}\right)$$

- Using the expressions for N_c, N_v from earlier:

$$\text{position of intrinsic Fermi level in the bandgap} \quad E_{Fi} = \frac{1}{2}(E_c + E_v) + \frac{3}{4}k_B T \ln\left(\frac{m_p^*}{m_n^*}\right)$$

- In the special case when $m_n^* = m_p^*$, the Fermi energy is precisely at the mid-gap energy. For $m_p^* > m_n^*$ it shifts to higher energies. For $m_p^* < m_n^*$ it shifts to lower energies.

$m_p^* > m_n^*$
FB toward Conduct band

Week 5

o Impurities

- Substitutional impurities
- Interstitial impurities

o Dopeant atoms

The fifth is loosely bound to the P atom; donor electron
a little energy to enter conduction band

→ n-type semiconductor

$$\# e^- > \# \text{hole}$$

The Group V atom is called donor impurity atom

e^- is majority mobile charge carrier

→ p-type semiconductor

$$\# \text{hole} > \# e^-$$

The Group III atom is called acceptor impurity atom

hole is majority mobile charge carrier

→ Extrinsic semiconductor

n-type & p-type are extrinsic Semiconductors

o Fermi level shifts depend on type of doping

n-type: Fermi level (E_F) move above the level ($E_{F,i}$)

p-type: ~~(E_F)~~ (E_F)

P-type

$E_F < E_{F,i}$

n-type

$E_F > E_{F,i}$

o Product of N_o and P_o remain constant

$$N_o P_o = N_n^2$$

o Relationship between N_o and P_o

~~Given electron Concentration (N_o)~~

$$N_o = N_c \exp\left(-\frac{(E_c - E_F)}{k_B T}\right)$$

N_c : effective density of states

Extrinsic semiconductors

- Note that our earlier expressions for n_0 and p_0 are still valid

$$n_0 = N_c \exp\left[\frac{-(E_c - E_F)}{k_B T}\right]$$

$$N_c = 2\left(\frac{2\pi m_n^* k_B T}{h^2}\right)^{3/2}$$

$$p_0 = N_v \exp\left[\frac{-(E_F - E_v)}{k_B T}\right]$$

$$N_v = 2\left(\frac{2\pi m_p^* k_B T}{h^2}\right)^{3/2}$$

extrinsic semi
 nFPs
 intrinsic semi,
 $n_0 = p_0$

- Earlier, we wrote out the product of n_0 and p_0 . For an intrinsic semiconductor, they were equal.
- This is no longer true for a doped semiconductor: $n_0 \neq p_0$

Extrinsic semiconductors

- So, we can just write:

$$\underline{n_0 p_0} = N_c N_v \exp\left[\frac{-(E_c - E_F)}{k_B T}\right] \exp\left[\frac{-(E_F - E_v)}{k_B T}\right] = N_c N_v \exp\left[\frac{-E_g}{k_B T}\right] = n_i^2$$

product → Constant

- Even though n_0 and p_0 are no longer equal, their product will still be:

AT T = 0 K

n-type No e⁻ in conduction band

$$n_0 p_0 = n_i^2 \quad \text{i} \rightarrow \text{intrinsic carrier concentration}$$

$$p_0 = \frac{n_i^2}{n_0}$$

P-type: No hole in valence band. All acceptor states are empty

- For a fixed semiconductor (Si, GaAs, Ge) and temperature, the product of n_0 and p_0 will always be the same regardless of how the semiconductor is doped

Extrinsic semiconductors

- If we know n_0 , we can find p_0 using:

$$n_0 = N_c \exp\left[\frac{-(E_c - E_{F_i})}{k_B T}\right] = N_c \exp\left[\frac{-(E_c - E_{F_i}) + (E_F - E_{F_i})}{k_B T}\right]$$

- We can also relate n_0 to n_i . Starting with the equation from Week 4, slide 23:

$$n_0 = N_c \exp\left[\frac{-(E_c - E_{F_i})}{k_B T}\right] \exp\left[\frac{(E_F - E_{F_i})}{k_B T}\right] = n_i \exp\left[\frac{(E_F - E_{F_i})}{k_B T}\right]$$

- A similar procedure can be applied to holes to obtain the following equation:

$$p_0 = n_i \exp\left[\frac{-(E_F - E_{F_i})}{k_B T}\right]$$

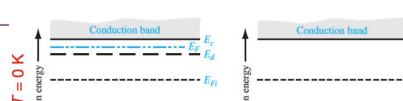
Concentration

T = 0 K vs room temperature

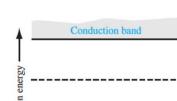
- At absolute zero (top two figures):

- All donor states in an *n*-type semiconductor are full
- All acceptor states in a *p*-type semiconductor are empty
- This is called *freeze out*

n-type:



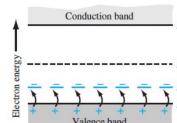
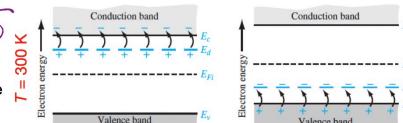
p-type:



- At room temperature (bottom two figures):

- All donor states in an *n*-type semiconductor are empty. The electrons have moved to the conduction band.
- All acceptor states in a *p*-type semiconductor are full. The electrons that have occupied these states leave behind holes in the valence band.
- This is called *complete ionization*

T = 300 K:



→ Compensated Semiconductors

Contain both donor and acceptor impurities are called
Compensated semi

n-type Compensated Semi : $N_d > N_a$

p-type Compensated Semi : $N_a > N_d$
Completely ~
: $N_a = N_d$

- For an *n*-type compensated semiconductor, we can show that the concentration of electrons in the conduction band will be:

Carrier Concentration in Compensated semi

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

- For a *p*-type compensated semiconductor, the concentration of holes in the valence band will be:

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

- The minority carrier concentration can always be calculated from: $n_0 p_0 = n_i^2$

Fermi energy

The Fermi energy in a compensated semiconductor

- The Fermi energy is influenced by the concentrations of both donor and acceptor atoms

- For an *n*-type compensated semiconductor:

Fermi Energy

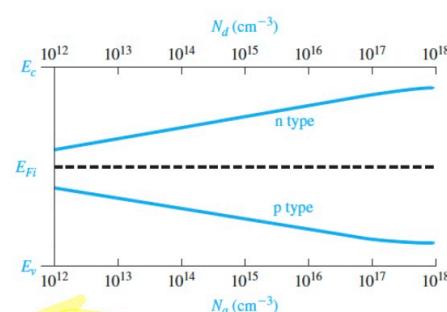
$$E_c - E_F = k_B T \ln\left(\frac{N_c}{n_0}\right)$$

- If $N_d \gg n$: $E_c - E_F = k_B T \ln\left(\frac{N_c}{N_d - N_a}\right)$

- For a *p*-type compensated semiconductor:

$$E_F - E_v = k_B T \ln\left(\frac{N_v}{p_0}\right)$$

- If $N_a \gg n$: $E_F - E_v = k_B T \ln\left(\frac{N_v}{N_a - N_d}\right)$



- In general, we need to find n_0 and p_0 using the expressions on the previous slide in order to find the Fermi energy

The Fermi energy in a compensated semiconductor

- In general, calculating the Fermi energy requires the following steps:

- Calculate N_c and N_v for the semiconductor of interest at the correct temperature
- Calculate n_0 and p_0 based on the concentrations of donor and/or acceptor impurities
- Calculate the Fermi energy using the equations on the previous slide

- Sometimes, we will need to calculate the position of the Fermi energy wrt the intrinsic Fermi energy. We can do so using the equations below.

- For an *n*-type semiconductor:

$$E_F - E_{Fi} = k_B T \ln\left(\frac{n_0}{n_i}\right)$$

- For a *p*-type semiconductor:

$$E_{Fi} - E_F = k_B T \ln\left(\frac{p_0}{n_i}\right)$$

position of fermi Energy
Relative to Intrinsic
Fermi Energy