ECE-305: Spring 2018
Exam 1 Review

Pierret, *Semiconductor Device Fundamentals* (SDF)
Chapters 1-3 (pp. 1-104)

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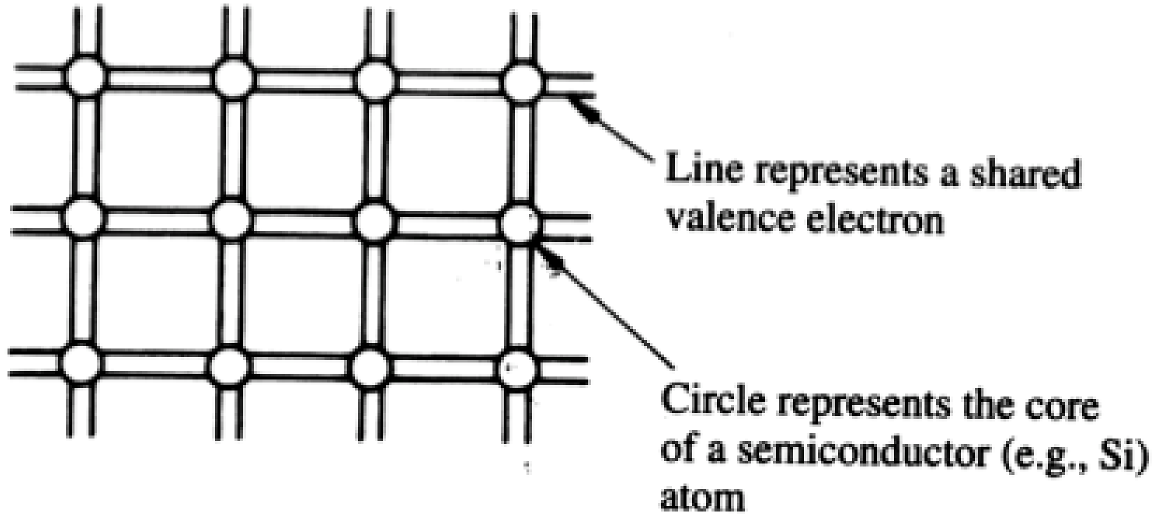
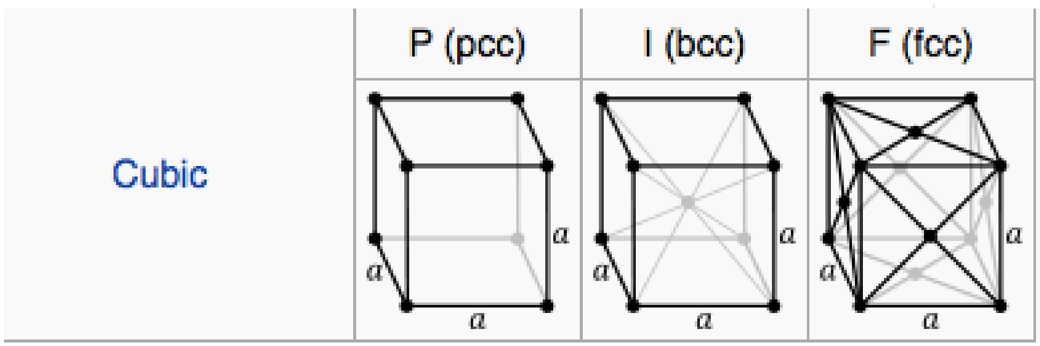
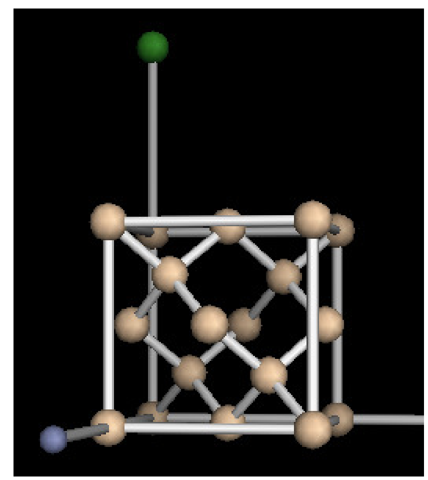
Key concepts

1. Crystal structures
2. Miller indices
3. Material types + band structures
4. Carrier concentrations
5. Mobility + resistivity
6. Drift-diffusion
7. P-N Junctions

Si crystals


Line represents a shared valence electron
Circle represents the core of a semiconductor (e.g., Si) atom


P (pcc)
I (bcc)
F (fcc)
Cubic
a



Miller indices

$\left(h\ k\ l\right)$ A specific plane.

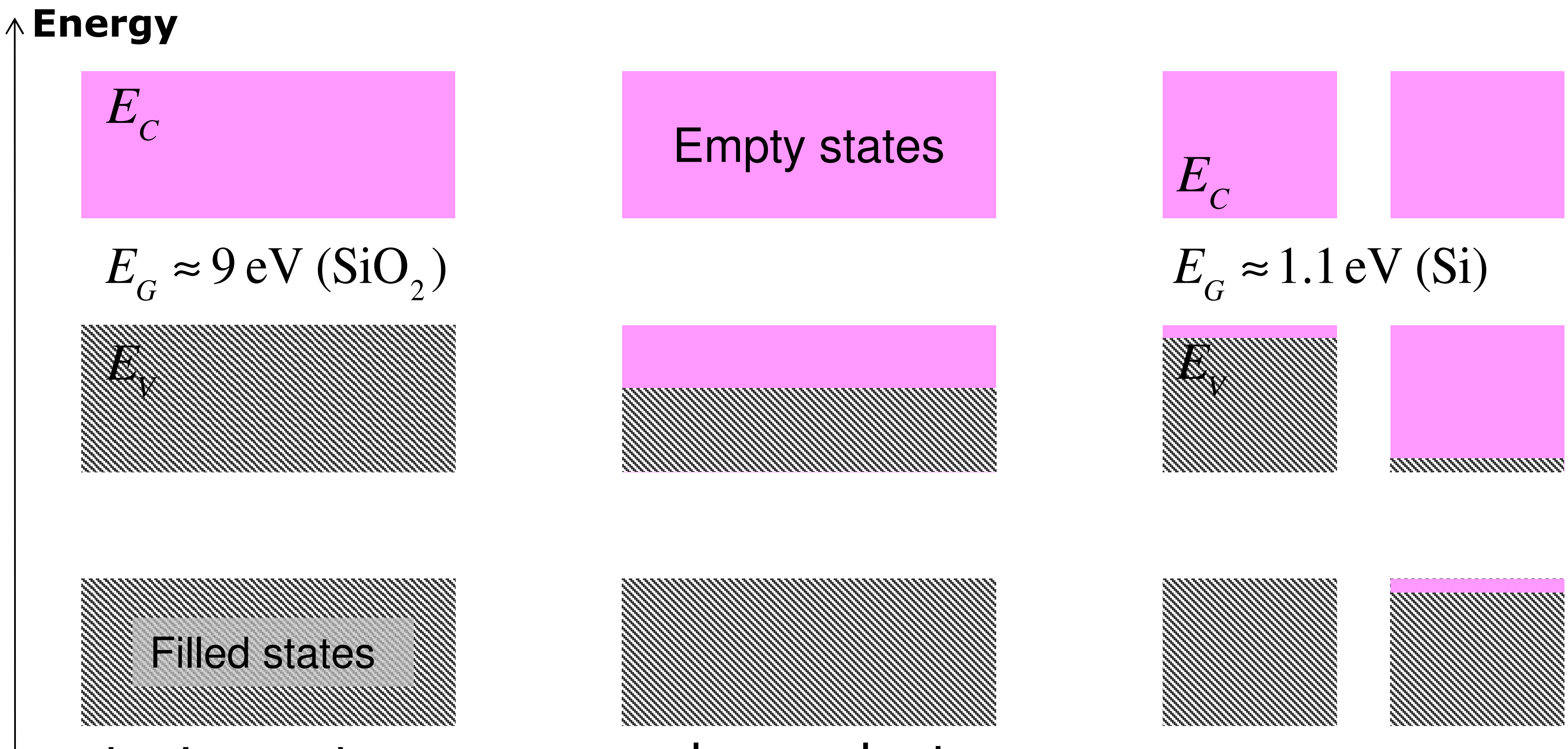
$\left[h\ k\ l\right]$ A direction normal to the plane above.

$$\vec{N} = ha\hat{x} + ka\hat{y} + la\hat{z}$$

$\left\{h\ k\ l\right\}$ A set of equivalent planes.

$\left\langle h\ k\ l\right\rangle$ A set of equivalent directions.

insulators | metals | semiconductors



don't conduct electricity well

do conduct electricity well

in-between, **but** can be controlled

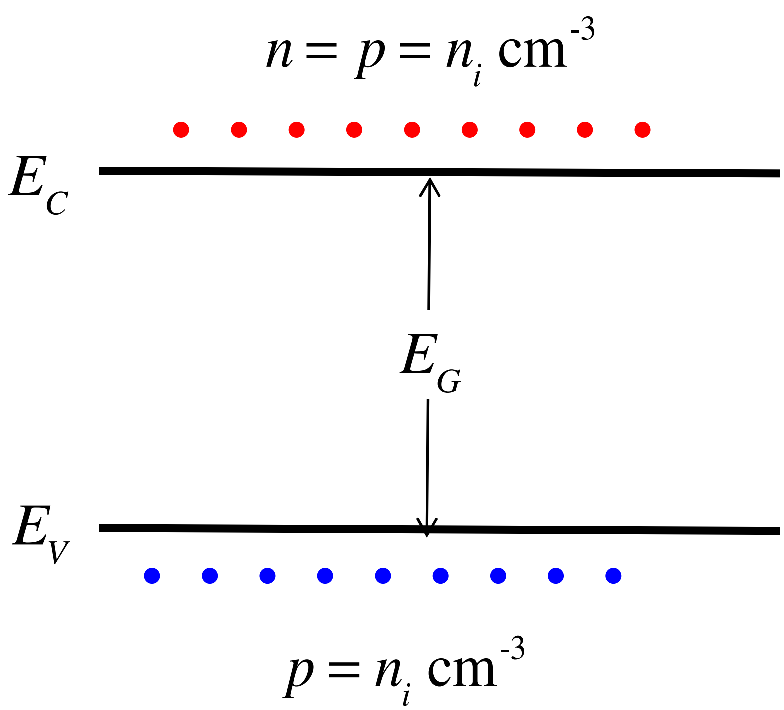
energy band diagrams

energy

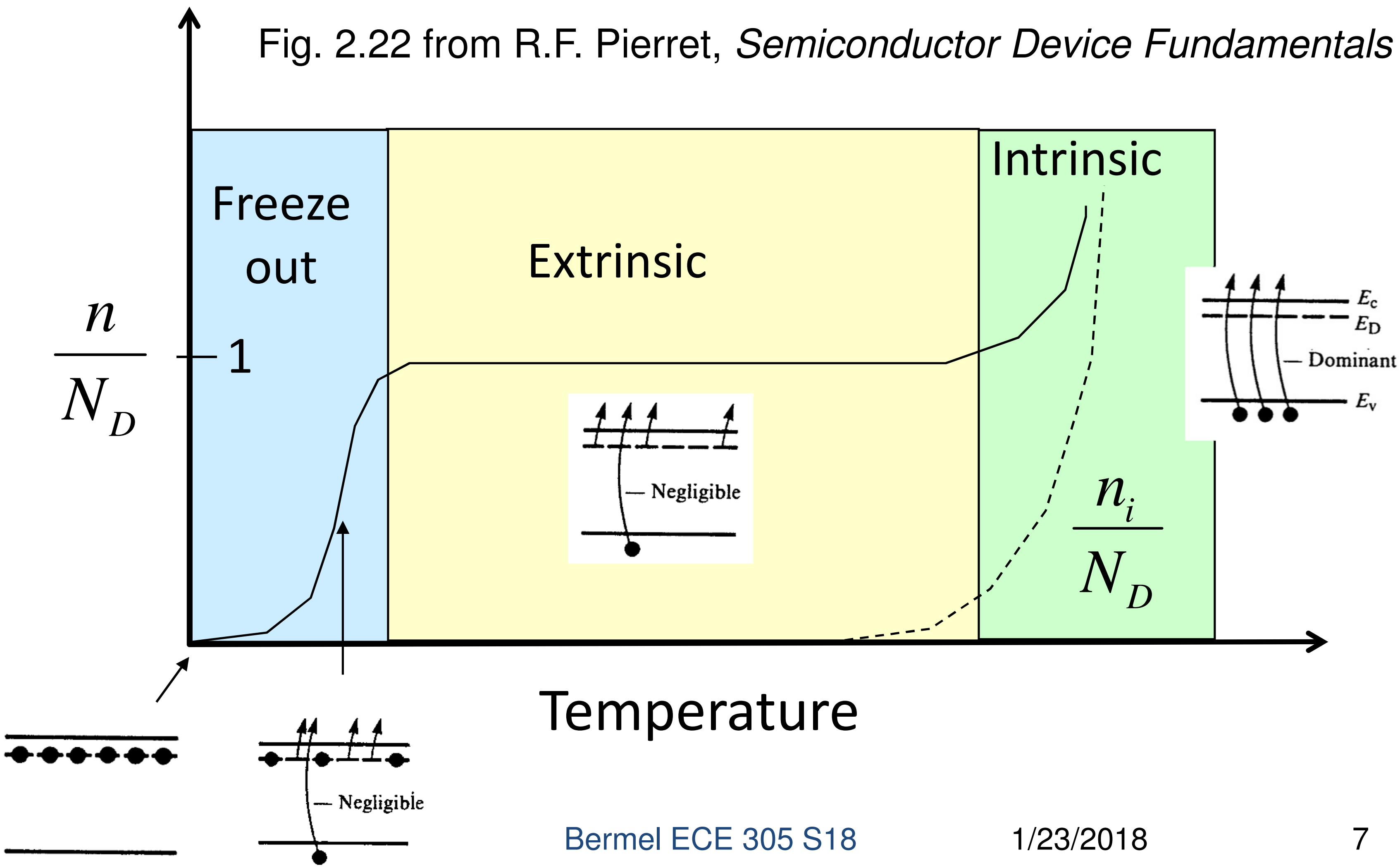
Conduction band: first partially empty band above filled valence band

"forbidden gap"

valence "band": highest filled band



Carrier concentration vs. temperature



Carrier Concentration in Intrinsic Semiconductors

$$n = p = n_i$$

$$n \times p = N_C e^{-(E_C - E_F)/k_B T} \times N_V e^{-(E_F - E_V)/k_B T}$$

$$= N_C N_V e^{-(E_C - E_V)/k_B T}$$

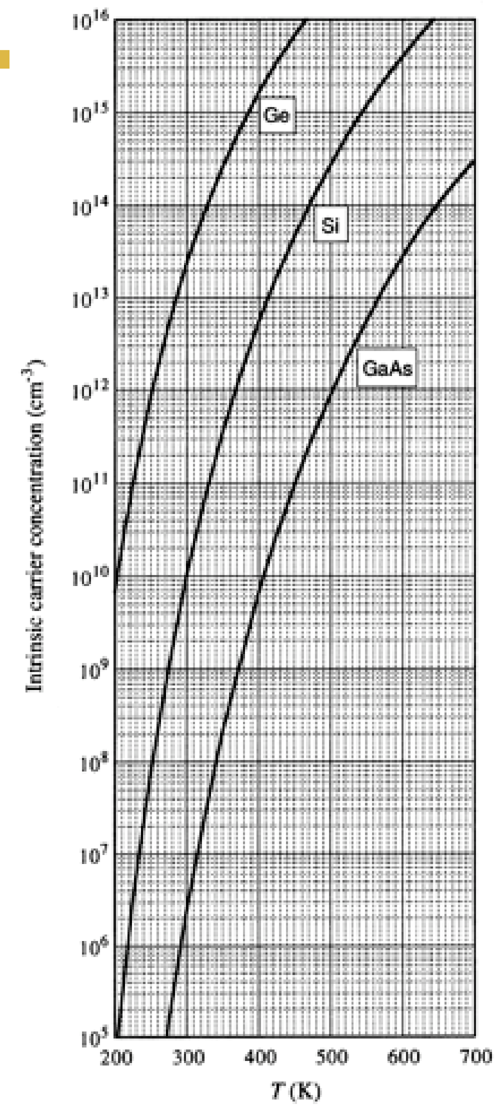
$$= N_C N_V e^{-E_g/k_B T}$$

$$= n_i^2$$

$$n_i = \sqrt{N_C N_V} e^{-E_g/2k_B T}$$

(Eq. from Ex. 2.4
Includes temp.-dependent
changes in effective mass)

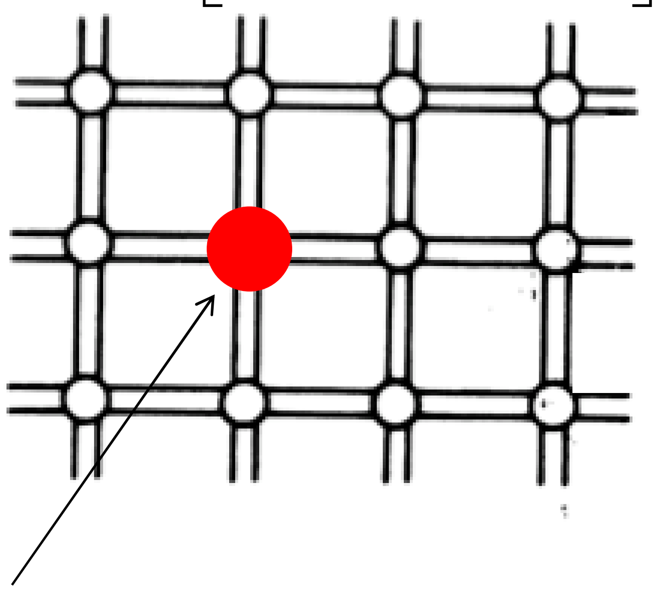
$$n_i(Si) = 9.15 \times 10^{19} \left(\frac{T}{300} \right)^2 e^{-1.12/2k_B T}$$



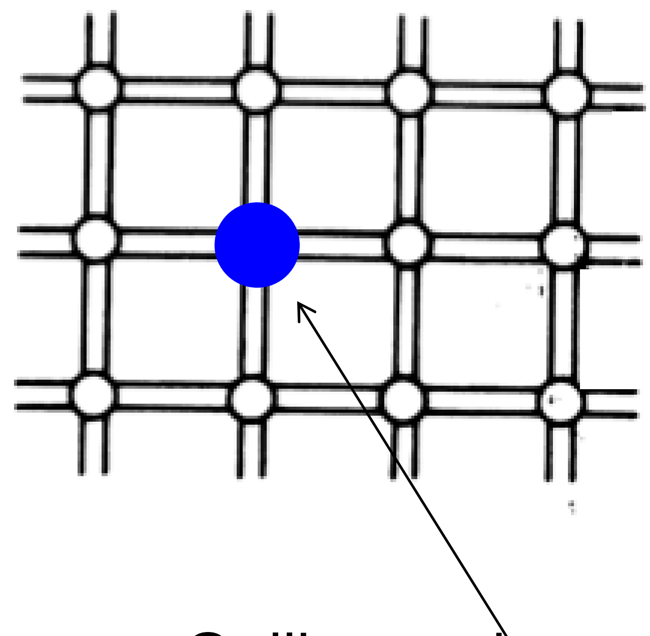
extrinsic doping

$$n = \frac{N_D - N_A}{2} + \left[\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2\right]^{1/2}$$

$$p = \frac{N_A - N_D}{2} + \left[\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2\right]^{1/2}$$

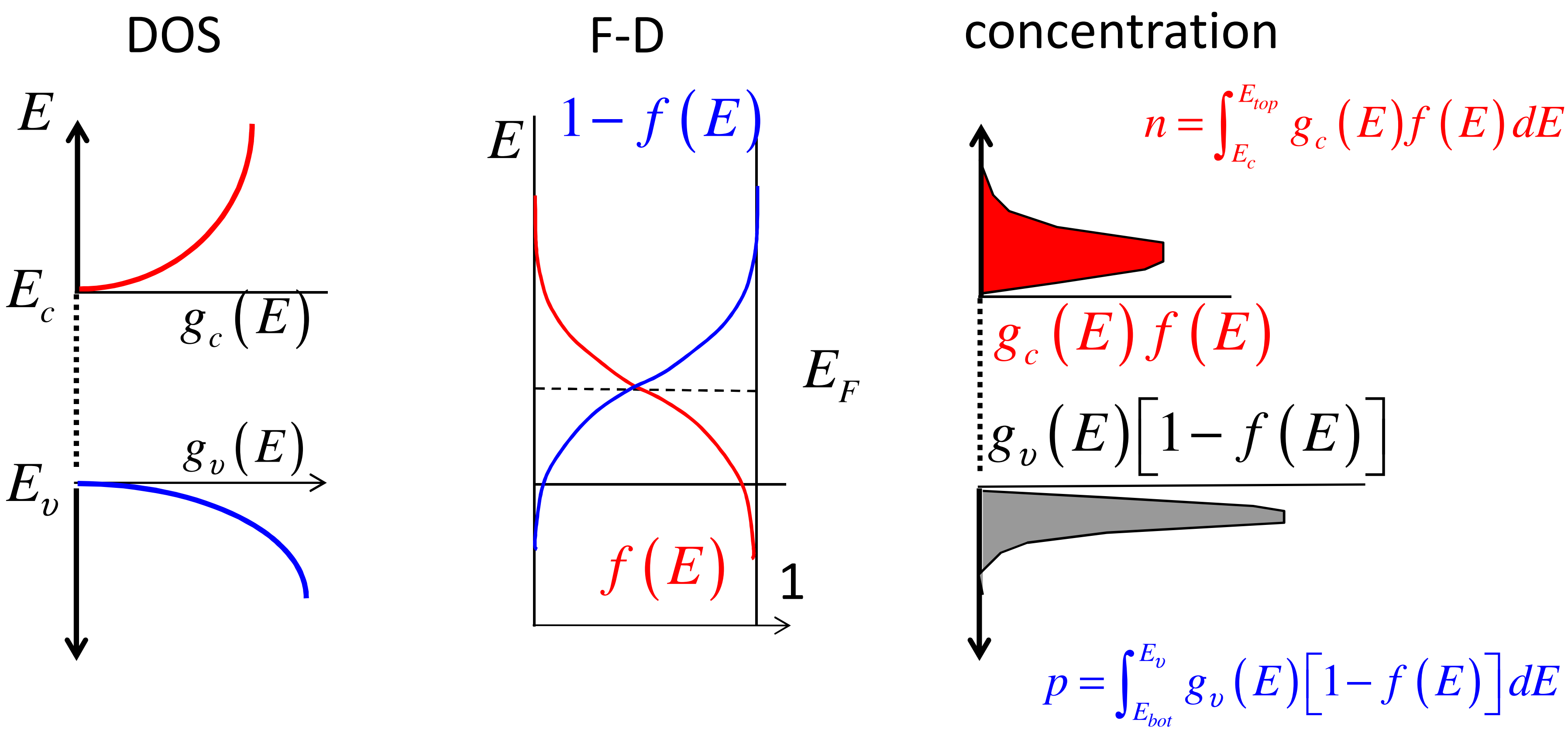


Phosphorus or Arsenic



Gallium or boron

Carrier Distribution



current, conductivity, resistivity

$$J_{nx} = nq\mu_n \mathcal{E}_x \text{ A/cm}^2 \qquad J_{nx} = \sigma_n \mathcal{E}_x \text{ A/cm}^2 \qquad \sigma_n = nq\mu_n \left(\text{units?}\right)$$

$$J_{px} = pq\mu_p \mathcal{E}_x \text{ A/cm}^2 \qquad J_{px} = \sigma_p \mathcal{E}_x \text{ A/cm}^2 \qquad \sigma_p = pq\mu_p$$

$$J_x = J_{nx} + J_{px} = \left(\sigma_n + \sigma_p\right)\mathcal{E}_x = \sigma \mathcal{E}_x \text{ A/cm}^2$$

$$J_x = \sigma \mathcal{E}_x \text{ A/cm}^2 \qquad \mathcal{E}_x = \frac{1}{\sigma} J_x = \rho J_x \text{ V/cm}$$

$$\rho = \frac{1}{\sigma} = \frac{1}{\sigma_n + \sigma_p} = \frac{1}{nq\mu_n + pq\mu_p} \ \Omega\text{-cm}$$

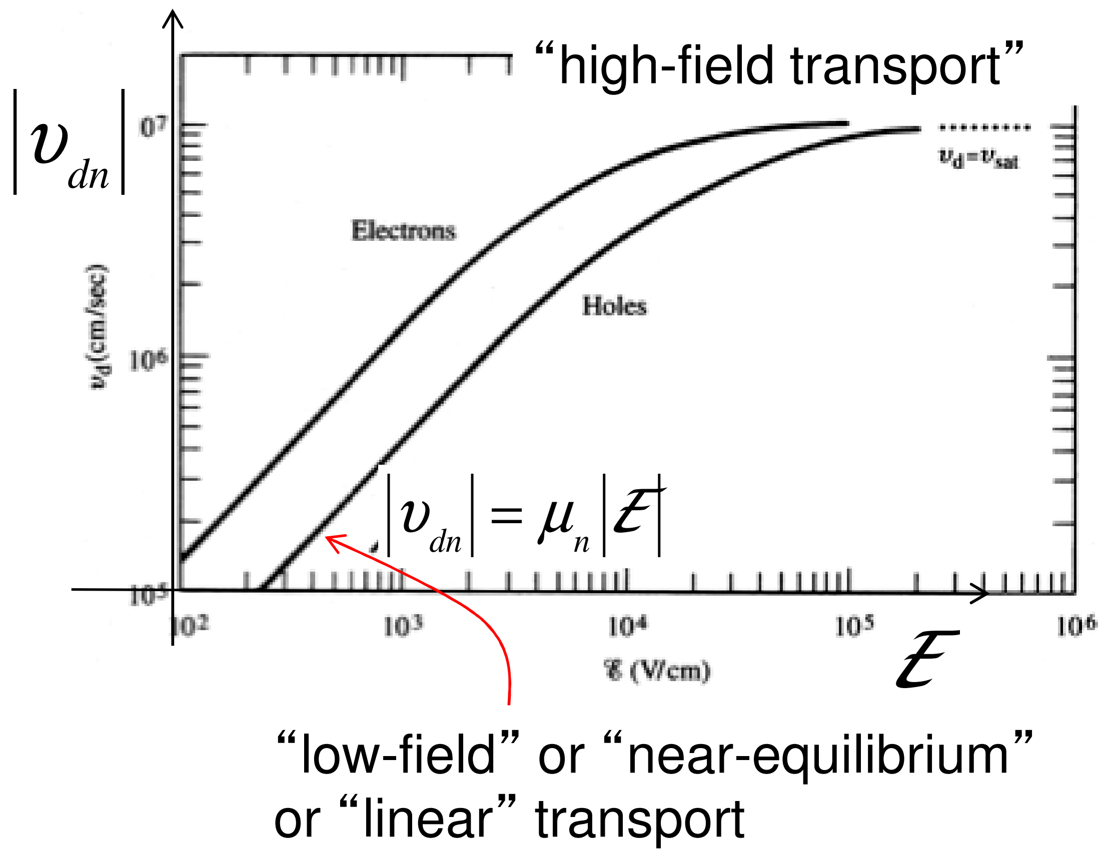
velocity and electric field

$$\upsilon_{dn} = -\mu_n \mathcal{E}$$

$$\mu_n = \left(\frac{q\tau}{m_n^*}\right) \text{cm}^2/\text{V-s}$$

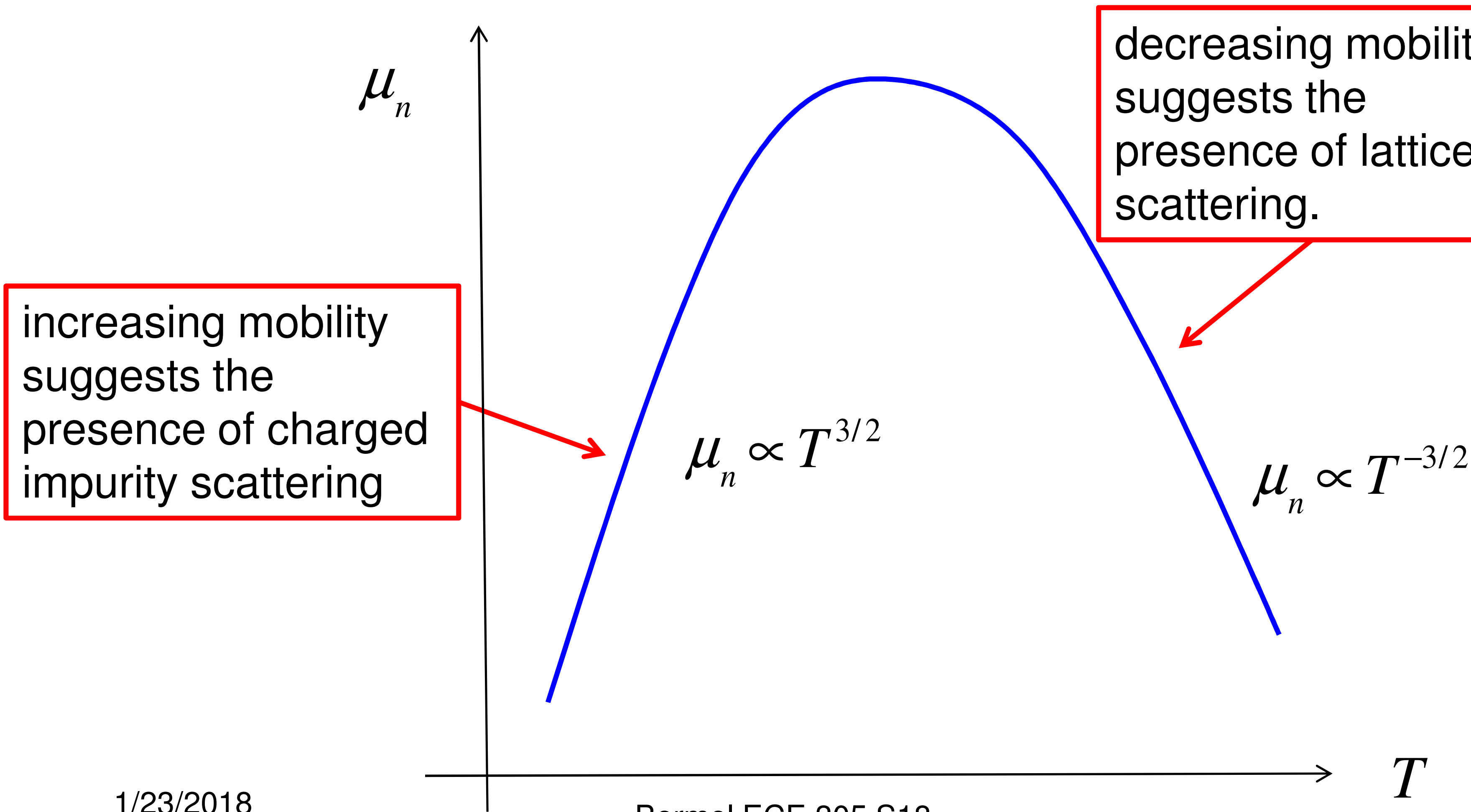
$$\upsilon_{dp} = +\mu_p \mathcal{E}$$

$$\mu_p = \left(\frac{q\tau}{m_p^*}\right) \text{cm}^2/\text{V-s}$$

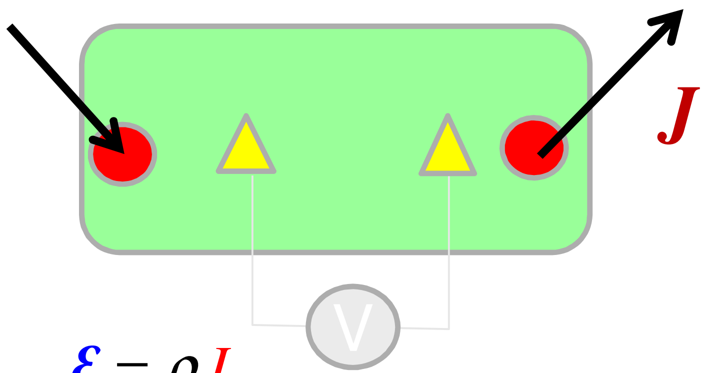


from R.F. Pierret, *Semiconductor Device Fundamentals,* Fig. 3.4

mobility vs. temperature



Doping dependent Resistivity



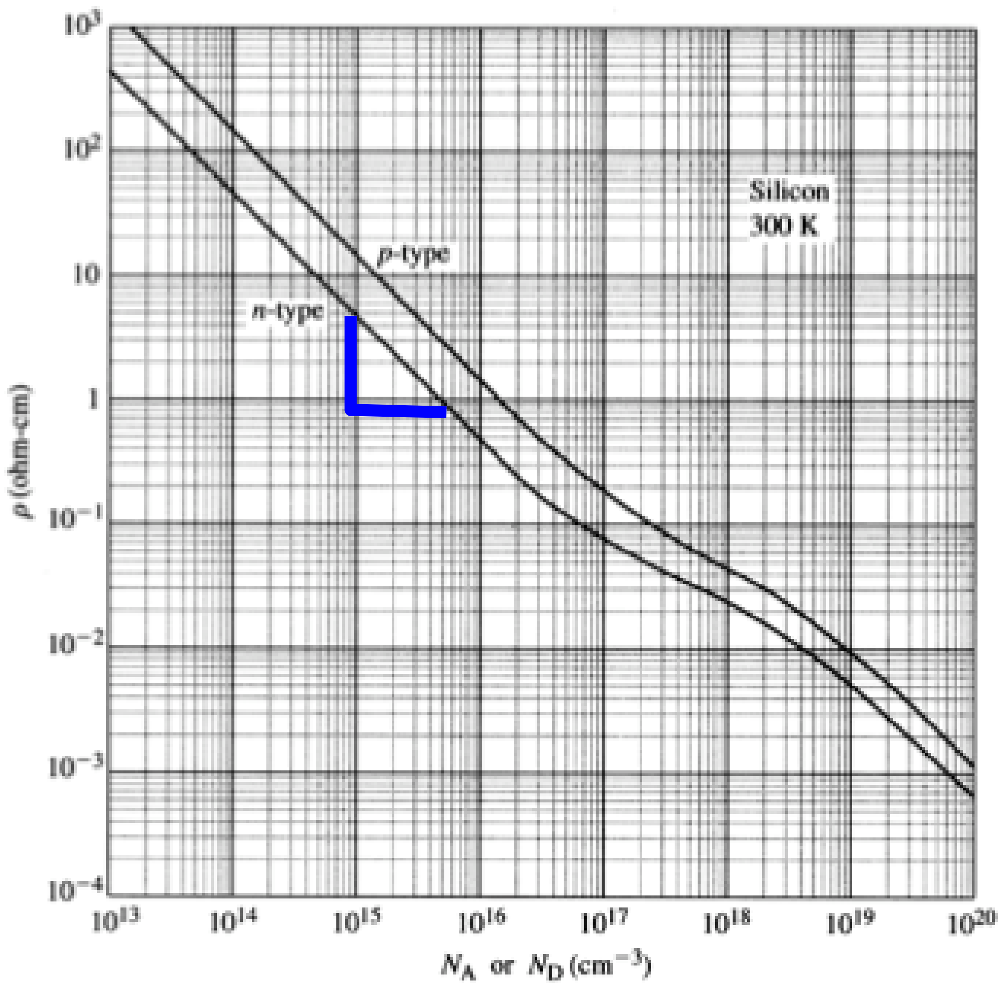
$$\mathcal{E} = \rho J$$

$$J = q(\mu_n n + \mu_p p)\mathcal{E}$$

$$\rho = \frac{1}{nq\mu_n + pq\mu_p}\ \Omega\text{-cm}$$

$$= \frac{1}{q\mu_n N_D} \text{ (for n-type)}$$

$$= \frac{1}{q\mu_p N_A}. \text{ (for p-type)}$$



drift- diffusion equation

$$\mu_p = \frac{q\tau}{m_p^*}$$

$$\mu_n = \frac{q\tau}{m_n^*}$$

$$D_p = \frac{\upsilon_{Tp}\ell_p}{2}$$

$$D_n = \frac{\upsilon_{Tn}\ell_n}{2}$$

$$\vec{J}_p = \vec{J}_{p-drift} + \vec{J}_{p-diff} = pq\mu_p\vec{\mathcal{E}} - qD_p\vec{\nabla}p$$

current = drift current + diffusion current

$$\vec{J}_n = \vec{J}_{n-drift} + \vec{J}_{n-diff} = nq\mu_n\vec{\mathcal{E}} + qD_n\vec{\nabla}n$$

total current = electron current + hole current

$$\vec{J} = \vec{J}_p + \vec{J}_n$$

$$D_p/\mu_p = D_n/\mu_n = k_BT/q$$

Exam 1 Formula Sheet

Physical Constants	Silicon parameters ($\boldsymbol{T} = \mathbf{300}$ K)
$\hbar = 1.055 \times 10^{-34}$ J·s	$N_C = 3.23 \times 10^{19}\ \mathrm{cm}^{-3}$
$m_0 = 9.109 \times 10^{-31}$ kg	$N_V = 1.83 \times 10^{19}\ \mathrm{cm}^{-3}$
$k = 1.38 \times 10^{-23}$ J/K	$n_i = 1.1 \times 10^{10}\ \mathrm{cm}^{-3}$
$q = 1.602 \times 10^{-19}$ C	$K_s = 11.8$
$\epsilon_0 = 8.854 \times 10^{-12}$ F/m	

Miller Indices: (hkl) {hkl} [hkl] <hkl>

Density of states $g_C(E) = \frac{(m_n^*)^{3/2}\sqrt{2(E-E_C)}}{\pi^2\hbar^3}$

Fermi function $f(E) = \frac{1}{1+e^{(E-E_F)/kT}}$

Intrinsic carrier concentration $n_i = \sqrt{N_C N_V} e^{-E_g/2kT}$

Equilibrium carrier densities: $N_C = \frac{1}{4}\left(\frac{2m_n^* kT}{\pi\hbar^2}\right)^{3/2}$

$N_V = \frac{1}{4}\left(\frac{2m_p^* kT}{\pi\hbar^2}\right)^{3/2}$

$n = N_C e^{(E_F-E_C)/kT} = n_i e^{(E_F-E_i)/kT}$

$p = N_V e^{(E_V-E_F)/kT} = n_i e^{(E_i-E_F)/kT}$

Exam 1 Formula Sheet

Space charge neutrality: $p - n + N_D^+ - N_A^- = 0$

Law of Mass Action: $np = n_i^2$

Conductivity/resistivity: $\sigma = \sigma_n + \sigma_p = q\left(n\mu_n + p\mu_p\right) = 1/\rho$

Drift-diffusion current equations:

$$J_n = nq\mu_n \mathcal{E}_x + qD_n \frac{dn}{dx} \qquad \frac{D_n}{\mu_n} = \frac{kT}{q}$$

$$J_p = pq\mu_p \mathcal{E}_x - qD_p \frac{dp}{dx} \qquad \frac{D_p}{\mu_p} = \frac{kT}{q}$$

Carrier conservation equations:

$$\frac{\partial n}{\partial t} = +\nabla \cdot \left(\frac{J_n}{q}\right) + G_n - R_n$$

$$\frac{\partial p}{\partial t} = -\nabla \cdot \left(\frac{J_p}{q}\right) + G_p - R_p$$

Poisson's equation:

$$\nabla \cdot (\epsilon \mathcal{E}) = \rho$$

Exam 1 Question 1 (Fall ‘16)

1 (8 points). What is the difference between a metal and a semiconductor?

a. Semiconductors have a zincblende lattice, while metals have a diamond lattice

b. Only a semiconductor can be polycrystalline

c. Only a metal can be polycrystalline

d. Only a semiconductor has an electronic bandgap

e. Only a metal has an electronic bandgap

Exam 1 Question 2 (Fall '16)

2 (8 points). What current is generated by holes diffusing down a concentration gradient?

a. $+qE$

b. $-qE$

c. $-q\ D_p\ dn/dx$

d. $+q\ D_n\ dp/dx$

e. $-q\ D_p\ dp/dx$

Exam 1 Question 3 (Fall ‘16)

3 (8 points). Where are donor and acceptor levels located on an energy band diagram?

a. Both are halfway between the conduction band minimum and valence band maximum.

b. Just above the conduction band minimum, and just below the valence band maximum, respectively.

c. Just below the conduction band minimum, and just above the valence band maximum, respectively.

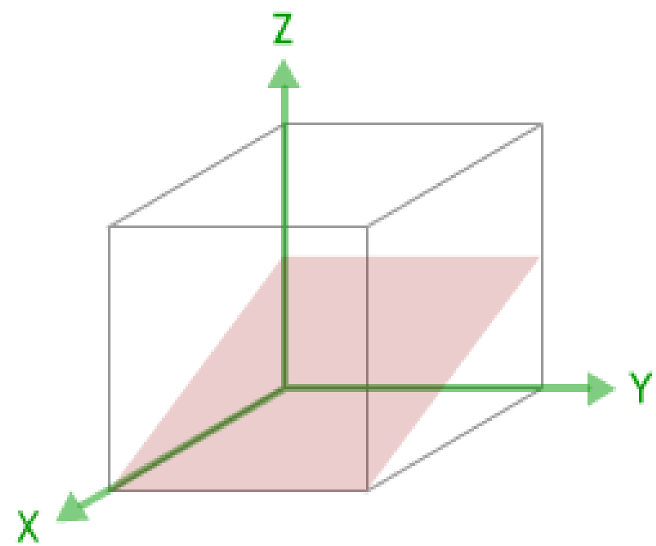
d. Well above the valence band maximum, and well above the conduction band minimum, respectively.

e. Donor and acceptor levels cannot be represented on an energy band diagram.

Exam 1 Question 4 (Fall '16)

4 (8 points). What is the Miller index for the plane shown below?

a. (201)
b. $(1\bar{1}1)$
c. (101)
d. (261)
e. (102)



Exam 1 Question 5 (Fall '16)

5 (8 points). What is the approximate conductivity of intrinsic crystalline silicon at $T = 300$ K? Note that $\mu_n = 1400$ cm^2/V·s, and $\mu_p = 450$ cm^2/V·s.

a. 326 S / cm

b. 3.26 S / cm

c. 3.26 mS / cm

d. 3.26 μS / cm

e. 3.26 nS / cm

Exam 1 Part II (Fall ‘16)

A p-type doped single-crystal wafer of germanium is at an elevated temperature ($T = 500$ K) with intrinsic carrier concentration $n_i = 2 \times 10^{16}$ cm^{-3}. Assume that under these conditions, the concentration of holes $p = 4 \times 10^{16}$ cm^{-3} everywhere.

a. For this sample, what is the electron concentration n (in units of cm^{-3})?

b. What is the concentration of acceptors in this material (in units of cm^{-3})? Assume that all acceptors are fully ionized, and that the concentration of donors $N_D = 2 \times 10^{16}$ cm^{-3}.

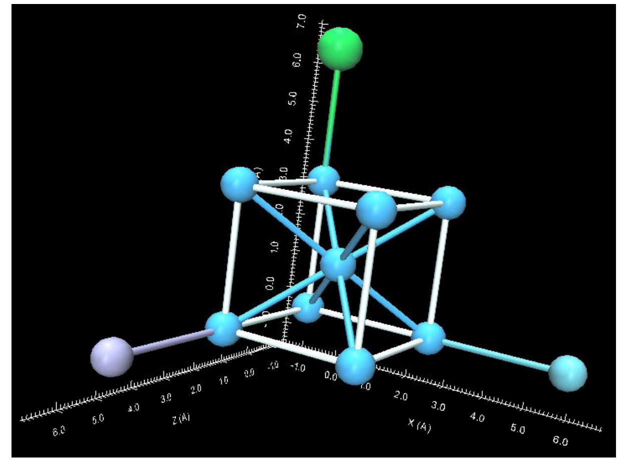
Exam 1 Part II (Fall '16)

c. Calculate where the Fermi level is located with respect to the valence band (in eV). Assume that $N_C = 2 \times 10^{19}\ \text{cm}^{-3}$ and $N_V = 10^{19}\ \text{cm}^{-3}$ under the given conditions.

d. Calculate where the Fermi level is located with respect to the intrinsic level (in eV).

Exam 1 Part III (Fall '16)

Assume that we have a body-centered cubic lattice of tungsten with an atomic radius of 1.37 Å and a periodicity of 3.1585 Å, as shown below (noting that 1 Å=10^{-8} cm).



a. Calculate the atomic density of this material (atoms/cm^3)

Exam 1 Part III (Fall '16)

b. Calculate the mass density of this material (g/cm^3). The atomic mass of tungsten is 183.84 amu, while $1 \text{ amu} = 1.66 \times 10^{-24}$ g.

c. Calculate the *packing fraction* of this material (i.e., the ratio of the total volume of the spheres to the volume of the cube enclosing them; a unitless value).

Conclusions

- Exam 1 takes place in class on Thursday, January 25
- Will be written to take 50 minutes, but you'll have at least 1 hour
- To do well, study Chapters 1-3; HW 1-2; Lectures 1-4; Exam 1 from prior semesters; and the notes from today