Lecture 2 - Carrier Statistics in Equilibrium

February 8, 2007

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Reading assignment:

del Alamo, Ch. 2, §§2.1-2.4 (2.4.1)

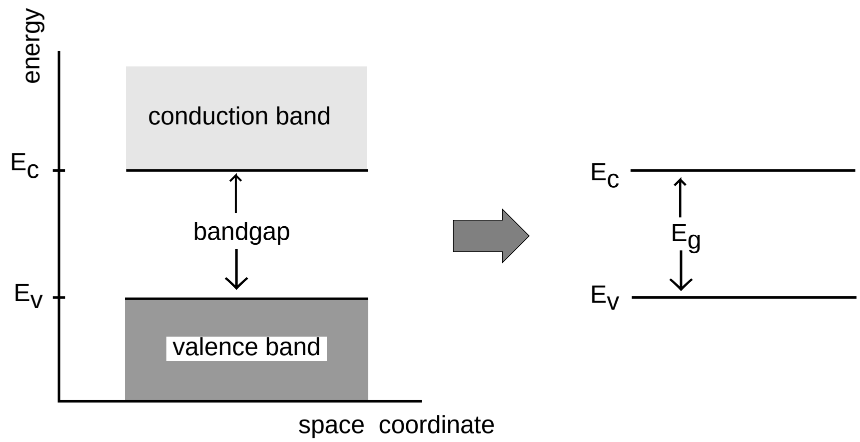
Announcement:

Go to http://ilab.mit.edu and register. Select membership in the 6.720 group. You will need this to access the lab for the Device Characterization Projects.

Key questions

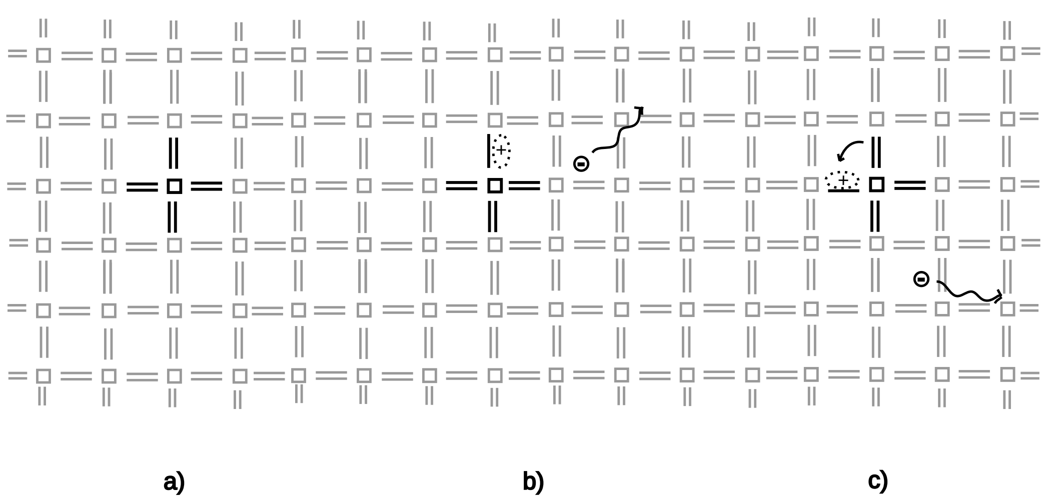
- What are these "energy band diagrams"?
- What are these "holes"?
- In a perfectly pure semiconductor, how many electrons and holes are there?
- Can one engineer the electron and hole concentrations in a semiconductor?

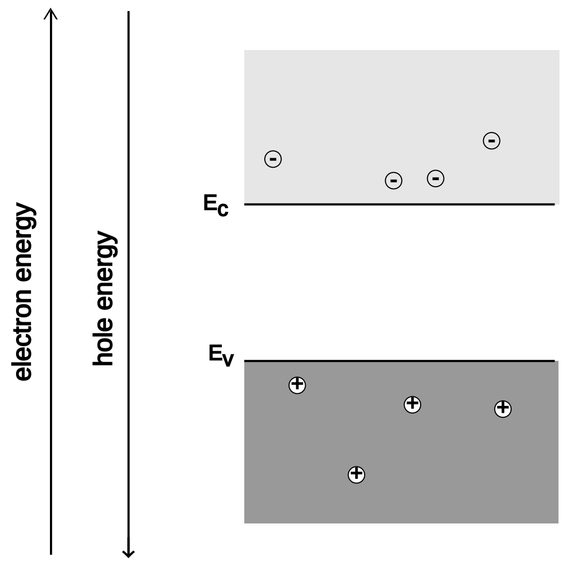
1. Conduction and valence bands, bandgap, holes



Conduction and valence bands:

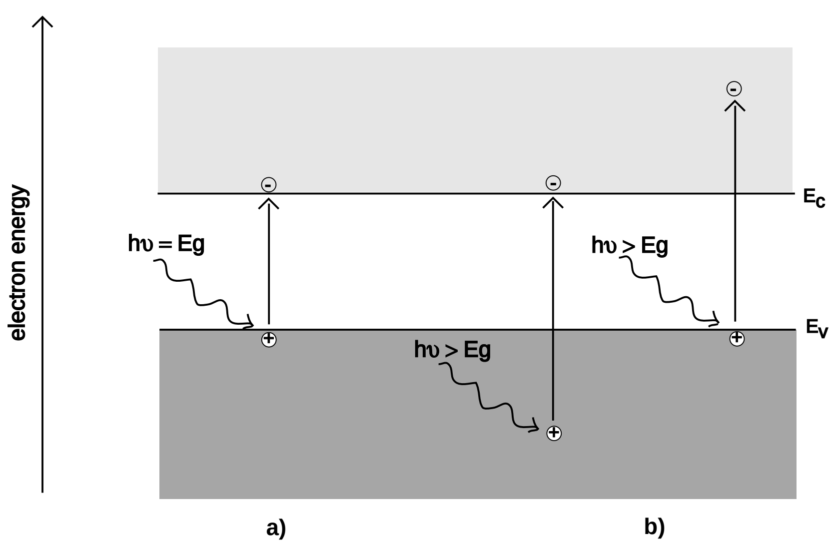
- *bonding electrons* occupy states in valence band
- *"free" electrons* occupy states in conduction band
- *holes*: empty states in valence band
- CB electrons and VB holes can move around: *"carriers"*





Elements of energy band diagrams:

- at edges of bands, kinetic energy of carriers is zero
- electron energies increase upwards
- hole energies increase downwards



2. Intrinsic semiconductor

Define *intrinsic semiconductor*, or "ideal" semiconductor:

- perfectly crystalline (no perturbations to periodic lattice)
- perfectly pure (no foreign atoms)
- no surface effects

Question: *How many electrons and holes are there in an intrinsic semiconductor in thermal equilibrium at a given temperature?*

Answer requires fairly elaborate model [lecture 3], but key dependencies can be readily identified.

Define:

$n_o \equiv$ equilibrium (free) electron concentration in conduction band $[cm^{-3}]$

$p_o \equiv$ equilibrium hole concentration in valence band $[cm^{-3}]$

Certainly in intrinsic semiconductor:

$$n_o = p_o = n_i$$

$$n_i \equiv \text{intrinsic carrier concentration } [cm^{-3}]$$

Key dependencies of n_i:

- *Temperature*:

$$T \uparrow \Rightarrow n_i$$

- *Bandgap*:

$$E_g \uparrow \Rightarrow n_i$$

What is detailed form of dependencies?

Use analogy of chemical reactions.

Electron-hole formation can be thought of as chemical reaction:

$$bond \rightleftharpoons e^- + h^+$$

similar to water decomposition reaction:

$$H_2O \rightleftharpoons H^+ + OH^-$$

Law-of-mass action relates concentration of reactants and reaction products. For water:

$$K = \frac{[H^+][OH^-]}{[H_2O]} \sim \exp(-\frac{E}{kT})$$

E is energy consumed or released in reaction.

This is a *"thermally activated" process* $\Rightarrow$ rate of reaction limited by need to overcome energy barrier E (*activation energy*).

In analogy, for electron-hole formation:

$$K = \frac{n_o p_o}{[bonds]} \sim \exp(-\frac{E_g}{kT})$$

$[bonds]$ is concentration of unbroken bonds.

Note: activation energy is E_g.

In general, relatively few bonds are broken. Hence:

$$[bonds] \gg n_o, p_o$$

and

$$[bonds] \simeq constant$$

Then:

$$n_o p_o \sim \exp(-\frac{E_g}{kT})$$

Two important results:

- First,

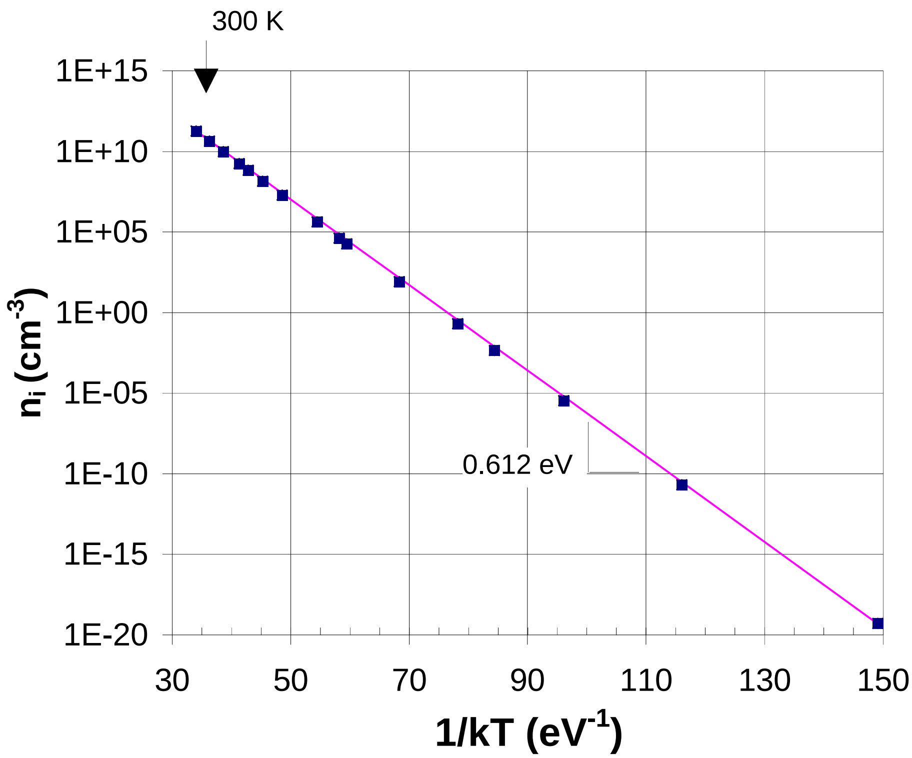
$$n_i \sim \exp(-\frac{E_g}{2kT})$$

As expected: $T \uparrow \Rightarrow n_i \uparrow$

$E_g \uparrow \Rightarrow n_i \downarrow$

To get prefactor, need detailed model [lecture 3].

Arrhenius plot for Si [experiments of Misiakos and Tsamakis, 1993]:



In Si at 300 K, $n_i \simeq 1.1 \times 10^{10}\ cm^{-3}$.

- Second important result:

$$n_o p_o = n_i^2$$

Equilibrium np product in a semiconductor at a certain temperature is a constant specific to the semiconductor.

3. Extrinsic semiconductor

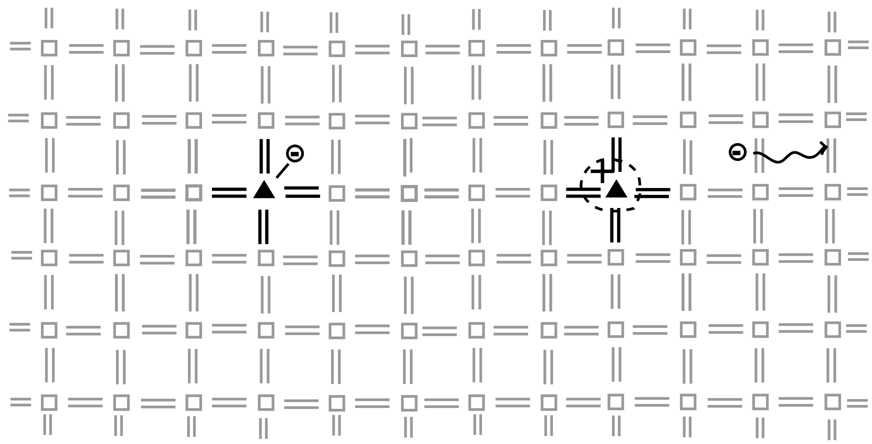
Can electron and hole concentrations be engineered?

Insert *dopants* in substitutional positions in the lattice:

- **Donors**: introduce electrons to conduction band without introducing holes to valence band
- **Acceptors**: introduce holes to valence band without introducing electrons to conduction band

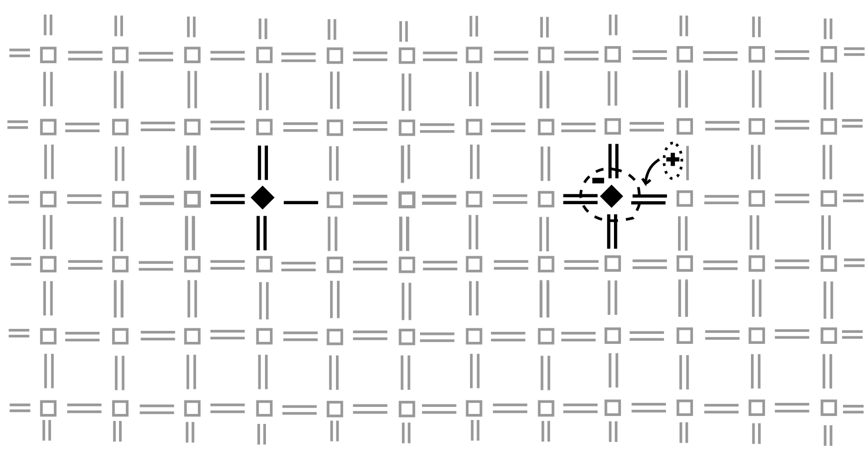
If any one carrier type overwhelms n_i $\Rightarrow$ extrinsic semiconductor

Donor in Si, atom from column V (As, P):



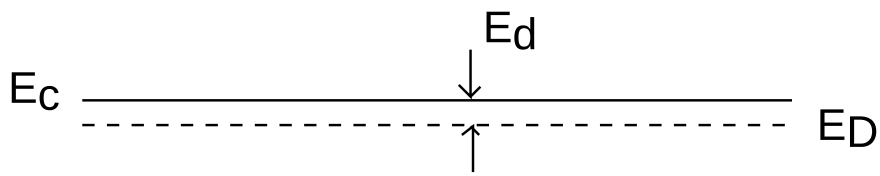
a) neutral donor b) ionized donor

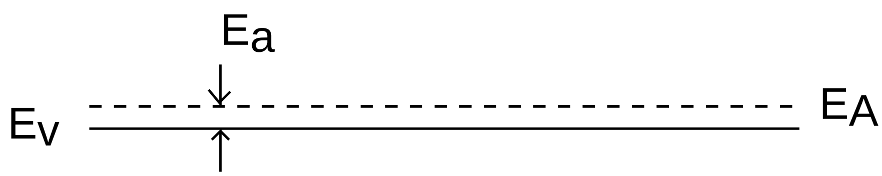
Acceptor in Si, atom from column III (B):



a) neutral acceptor b) ionized acceptor

Representation of donor and acceptor states in energy band diagram:





$E_d, E_a \sim 40 - 60\ meV$, for common dopants

□ Near room temperature, all dopants are ionized:

$$N_D^+ \simeq N_D$$

$$N_A^- \simeq N_A$$

Typical doping levels:

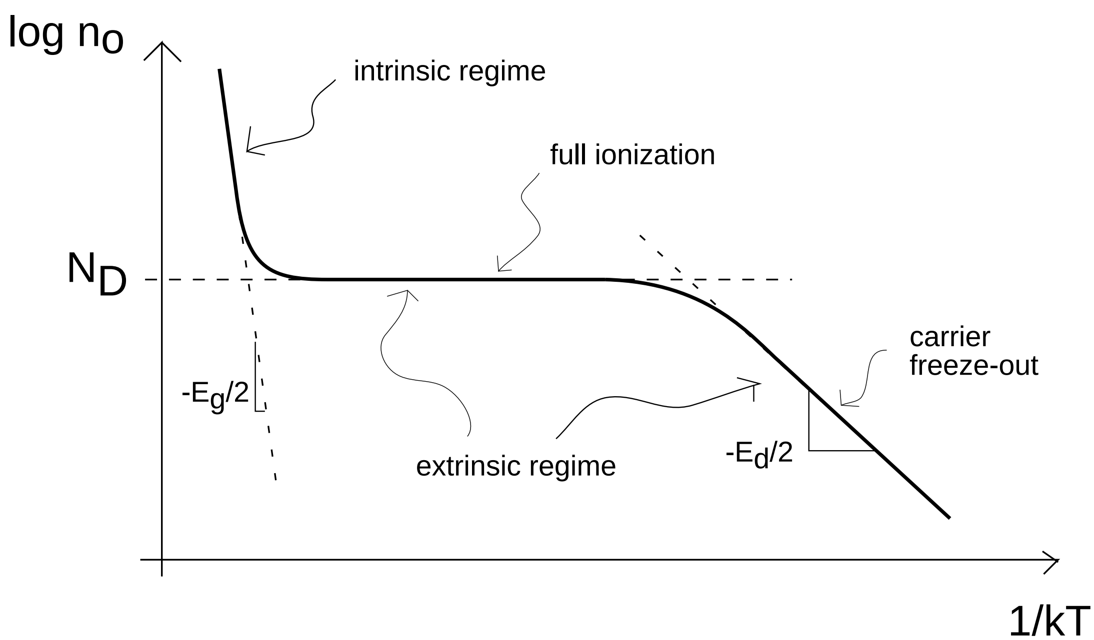
$$N_A, N_D \sim 10^{15} - 10^{20}\ cm^{-3}$$

□ n-type semiconductor

$$n_o \simeq N_D$$

$$p_o \simeq \frac{n_i^2}{N_D}$$

These equations are valid at intermediate temperatures.



□ p-type semiconductor

$$p_o \simeq N_A$$

$$n_o \simeq \frac{n_i^2}{N_A}$$

4. Conduction and valence band density of states

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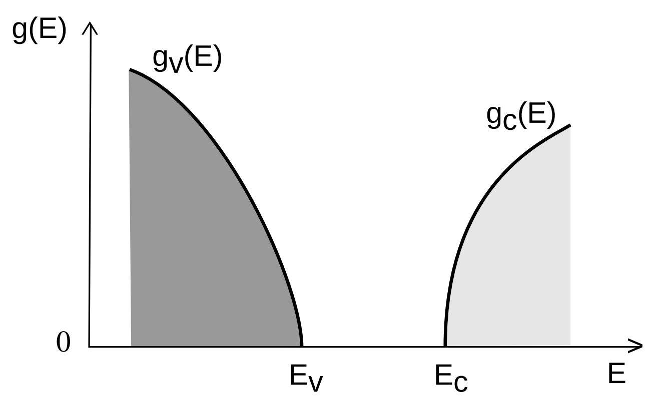
Figure 1b) on p. 468 in Laux, S. E., M. V. Fischetti, and D. J. Frank. "Monte Carlo Analysis of Semiconductor Devices: The DAMOCLES Program." *IBM Journal of Research and Development* 34, no. 4 (Jul. 1990): 466-494.

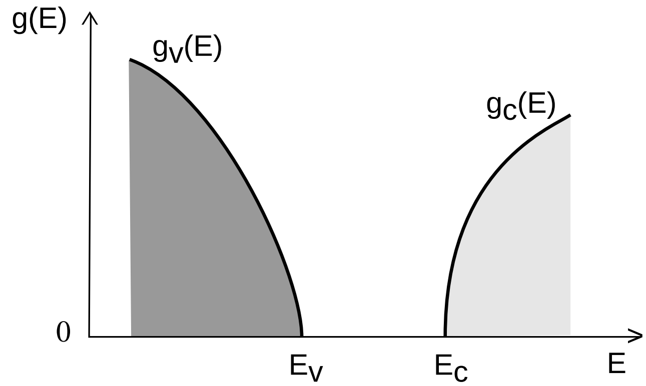
Can also be found in Fischetti, M. V., and S. E. Laux. "Monte Carlo Simulation of Submicron Si MOSFETs." In *Simulation of Semiconductor Devices and Processes.* Vol. 3.: Proceedings of the Third International Conference on Simulation of Semiconductor Devices and Processes, held at the University of Bologna, Bologna, Italy, on September 26th-28th, 1988. Edited by G. Baccarani and M. Rudan. Bologna, Italy: Technoprint, 1988, pp. 349-368.

Close to edges:

$$g_c(E) \propto \sqrt{E - E_c} \qquad E \geq E_c$$

$$g_v(E) \propto \sqrt{E_v - E} \qquad E \leq E_v$$





Common expressions for DOS:

$$g_c(E) = 4\pi \left(\frac{2m^*_{de}}{h^2}\right)^{3/2} \sqrt{E - E_c} \qquad E \geq E_c$$

$$g_v(E) = 4\pi \left(\frac{2m^*_{dh}}{h^2}\right)^{3/2} \sqrt{E_v - E} \qquad E \leq E_v$$

$m^*_{de} \equiv$ density of states electron effective mass
$m^*_{dh} \equiv$ density of states hole effective mass

Key conclusions

- Concept of *(free) electron*: electron in conduction band.
- Concept of *hole*: empty state in valence band.
- *Intrinsic semiconductor*: ideally pure semiconductor.

$$n_o = p_o = n_i \sim \exp(-\frac{E_g}{2kT})$$

- To first order, for a given semiconductor $n_o p_o$ is a constant that only depends on T:

$$n_o p_o = n_i^2$$

- Equilibrium carrier concentrations can be engineered through *shallow dopants* $\Rightarrow$ *extrinsic semiconductor*.
  - n-type semiconductor:

$$n_o \simeq N_D, \qquad p_o \simeq \frac{n_i^2}{N_D}$$

  - p-type semiconductor:

$$p_o \simeq N_A, \qquad n_o \simeq \frac{n_i^2}{N_A}$$

- Around edges, conduction and valence bands in semiconductors feature $DOS \sim \sqrt{E}$.
- Order of magnitude of key parameters for Si at 300 K:
  - intrinsic carrier concentration: $n_i \sim 10^{10}\ cm^{-3}$
  - typical doping level range: $N_D,\ N_A \sim 10^{15} - 10^{20}\ cm^{-3}$

Self study

- Charge neutrality