Lecture 2 - Semiconductor Physics (I)

February 8, 2001

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Reading assignment:

Howe and Sodini, Ch. 2, §§2.1-2.3

Key questions

- How do semiconductors conduct electricity?
- What is a "hole"?
- How many electrons and holes are there in a semiconductor in thermal equilibrium at a certain temperature?
- How can one engineer the conductivity of semiconductors?

1. Silicon bond model: electrons and holes

Si is in Column IV of periodic table:

IIB	IIIA	IVA	VA	VIA
	5 B	6 C	7 N	8 O
	13 Al	14 Si	15 P	16 S
30 Zn	31 Ga	32 Ge	33 As	34 Se
48 Cd	49 In	50 Sn	51 Sb	52 Te

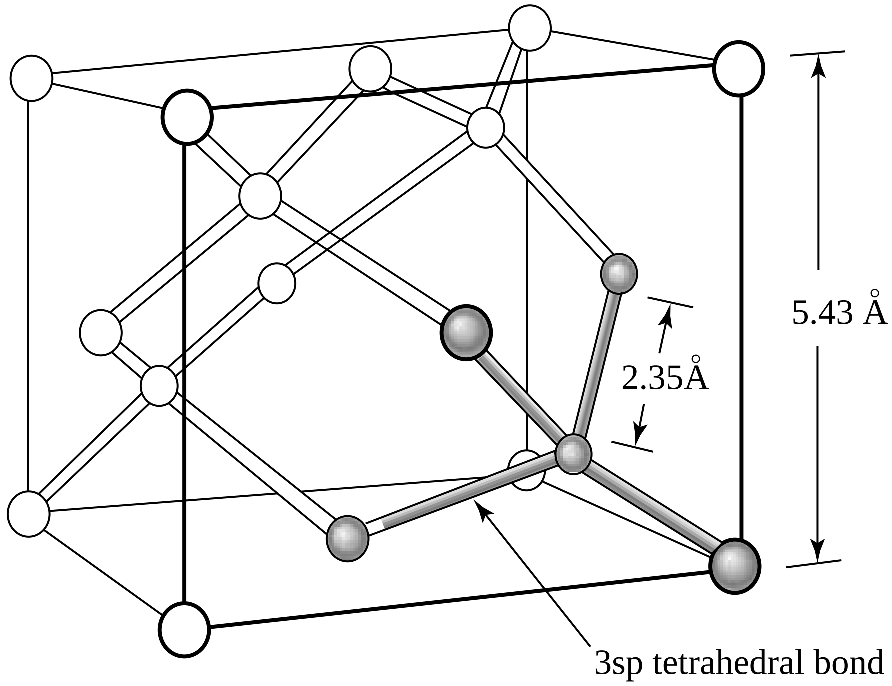
Electronic structure of Si atom:

- 10 core electrons (tightly bound)
- 4 valence electrons (loosely bound, responsible for most chemical properties)

Other semiconductors:

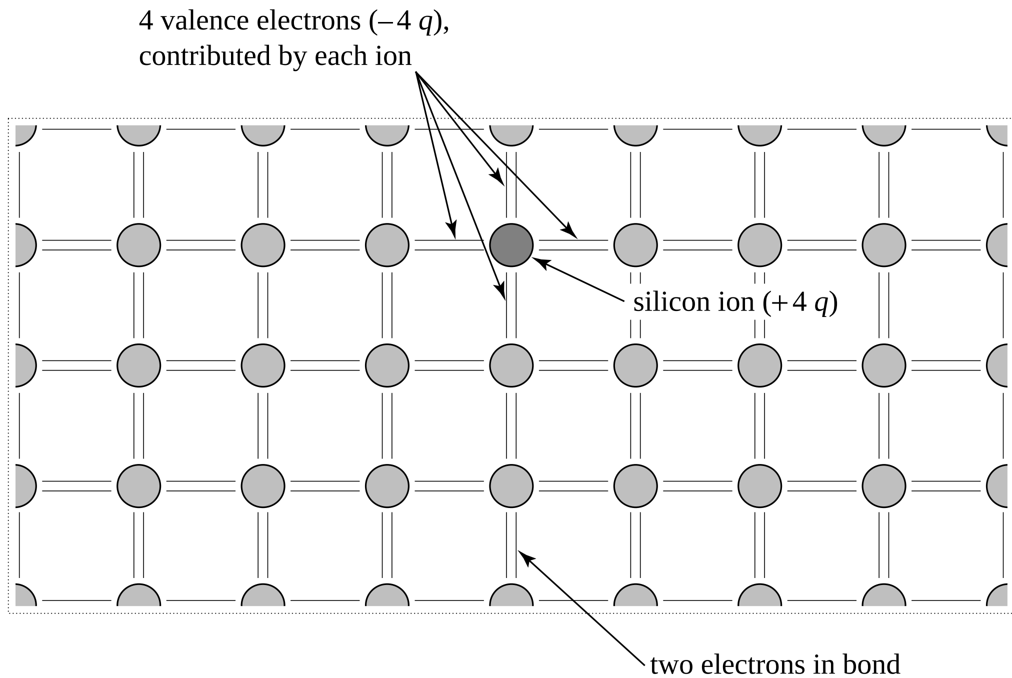
- Ge, C (diamond form),
- GaAs, InP, InGaAs, InGaAsP, ZnSe, CdTe
  (on average, 4 valence electrons per atom)

Silicon crystal structure:



- Diamond lattice: atoms tetrahedrally bonded by sharing valence electrons (*covalent bonding*)
- Each atom shares 8 electrons (low energy situation)
- Si atomic density: $5 \times 10^{22}\ cm^{-3}$

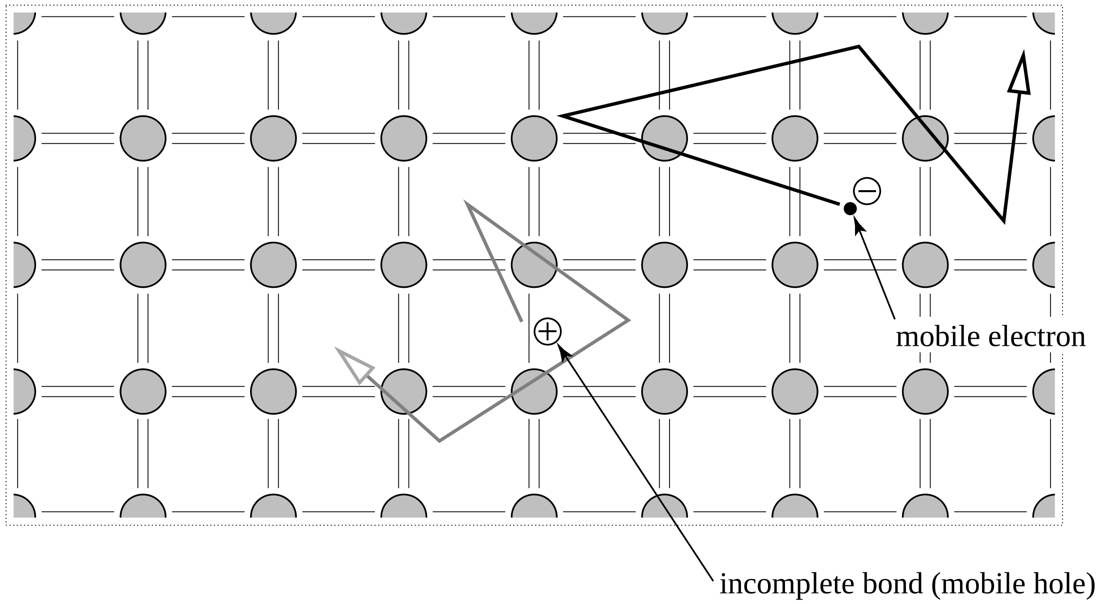
Simple ”flattened” model of Si crystal:



At 0K:

- all bonds satisfied → all valence electrons engaged in bonding
- no ”free” electrons

At finite temperature:



- finite thermal energy
- some bonds are broken
- "free" electrons (mobile negative charge, $-1.6\times10^{-19}\,C$)
- "free" *holes* (mobile positive charge, $1.6\times10^{-19}\,C$)

"Free" electrons and holes are called *carriers*: mobile charged particles.

Beware: picture is misleading!
Electrons and holes in semiconductors are "fuzzier": they span many atomic sites.

A few definitions:

- in 6.012, "electron" means <u>free</u> electron
- not concerned with bonding electrons or core electrons
- define:

$$n \equiv \text{(free) electron concentration } [cm^{-3}]$$

$$p \equiv \text{hole concentration } [cm^{-3}]$$

2. Generation and Recombination

GENERATION = break up of covalent bond to form electron and hole

- requires energy from thermal or optical sources (or other external sources)
- *generation rate*: $G = G_{th} + G_{opt} + ...\ [cm^{-3} \cdot s^{-1}]$
- in general, *atomic density* $\gg n,\ p\ \Rightarrow$

$$G \neq f(n, p)$$

(supply of breakable bonds virtually inexhaustible)

RECOMBINATION = formation of bond by bringing together electron and hole

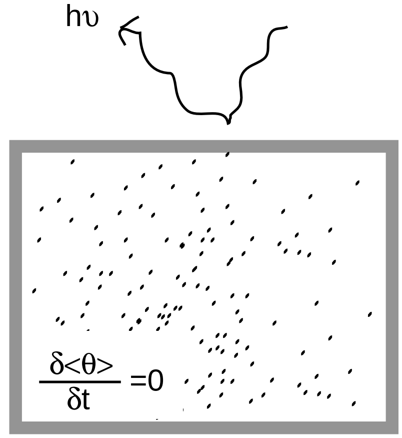
- releases energy in thermal or optical form
- *recombination rate*: $R\ [cm^{-3} \cdot s^{-1}]$
- a recombination event requires 1 electron + 1 hole $\Rightarrow$

$$R \propto n \cdot p$$

Generation and recombination most likely at surfaces where periodic crystalline structure is broken.

3. Thermal equilibrium

THERMAL EQUILIBRIUM =
steady state + absence of external energy sources



- Generation rate in thermal equilibrium: $G_o = f(T)$
- Recombination rate in thermal equilibrium: $R_o \propto n_o \cdot p_o$

In thermal equilibrium:

$$G_o = R_o \Rightarrow n_o p_o = f(T) \equiv n_i^2(T)$$

Important consequence:

In thermal equilibrium and for a given semiconductor, np product is a constant that depends only on temperature!

Electron-hole formation can be seen 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:

$$K = \frac{[H^+][OH^-]}{[H_2O]}$$

Since:

$$[H_2O] \gg [H^+],\ [OH^-]$$

Then:

$$[H_2O] \simeq constant$$

Hence:

$$[H^+][OH^-] \simeq constant$$

4. Intrinsic semiconductor

QUESTION: In a perfectly pure semiconductor in thermal equilibrium at finite temperature, how many electrons and holes are there?

Since when a bond breaks, an electron *and* a hole are produced:

$$n_o = p_o$$

Also:

$$n_o p_o = n_i^2$$

Then:

$$n_o = p_o = n_i$$

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

In Si at 300 K ("room temperature"): $n_i \simeq 1 \times 10^{10}\ cm^{-3}$

n_i very strong function of temperature: $T \uparrow \rightarrow n_i \uparrow$

Note: an intrinsic semiconductor need not be perfectly pure [see next]

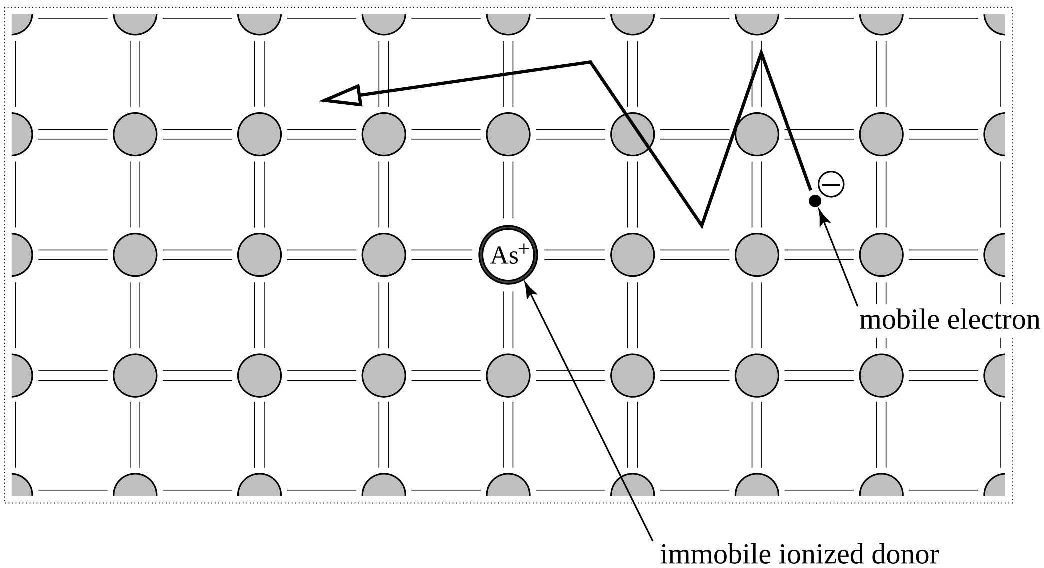
5. Doping: introduction of foreign atoms to engineer semiconductor electrical properties

A. DONORS: introduce electrons to the semiconductor (but not holes)

- For Si, group-V atoms with 5 valence electrons (As, P, Sb)

IIB	IIIA	IVA	VA	VIA
	5 B	6 C	7 N	8 O
	13 Al	14 Si	15 P	16 S
30 Zn	31 Ga	32 Ge	33 As	34 Se
48 Cd	49 In	50 Sn	51 Sb	52 Te

- 4 electrons of donor atom participate in bonding
- 5th electron easy to release $\Rightarrow$ at room temperature, each donor releases 1 electron that is available to conduction
- donor site become positively charged (fixed charge)



Define:

$$N_d \equiv \text{donor concentration } [cm^{-3}]$$

- If $N_d \ll n_i$, doping irrelevant

($intrinsic$ semiconductor) $\rightarrow n_o = p_o = n_i$

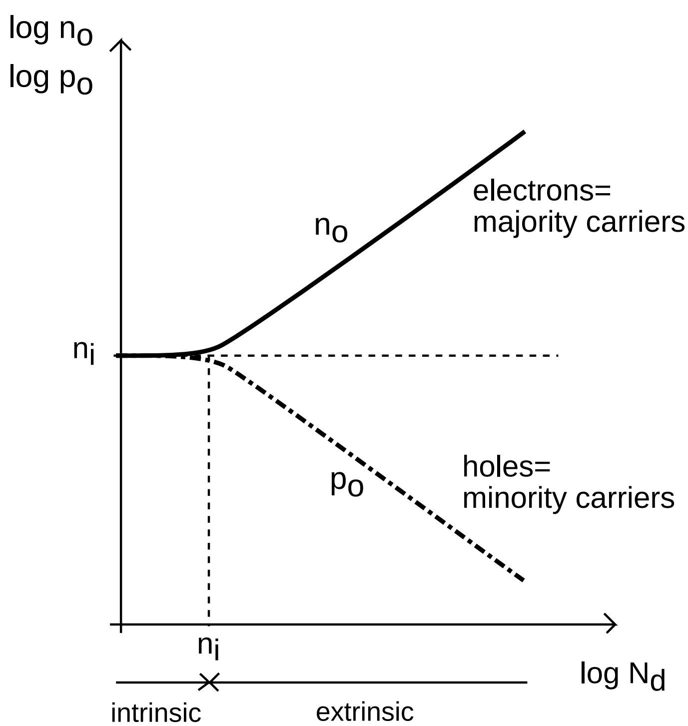
• If $N_d \gg n_i$, doping controls carrier concentrations (*extrinsic* semiconductor) →

$$n_o = N_d \qquad\qquad p_o = \frac{n_i^2}{N_d}$$

Note: $n_o \gg p_o$: *n-type semiconductor*

Example:
$N_d = 10^{17}\ cm^{-3} \rightarrow n_o = 10^{17}\ cm^{-3}$, $p_o = 10^3\ cm^{-3}$.

In general: $N_d \sim 10^{15} - 10^{20}\ cm^{-3}$



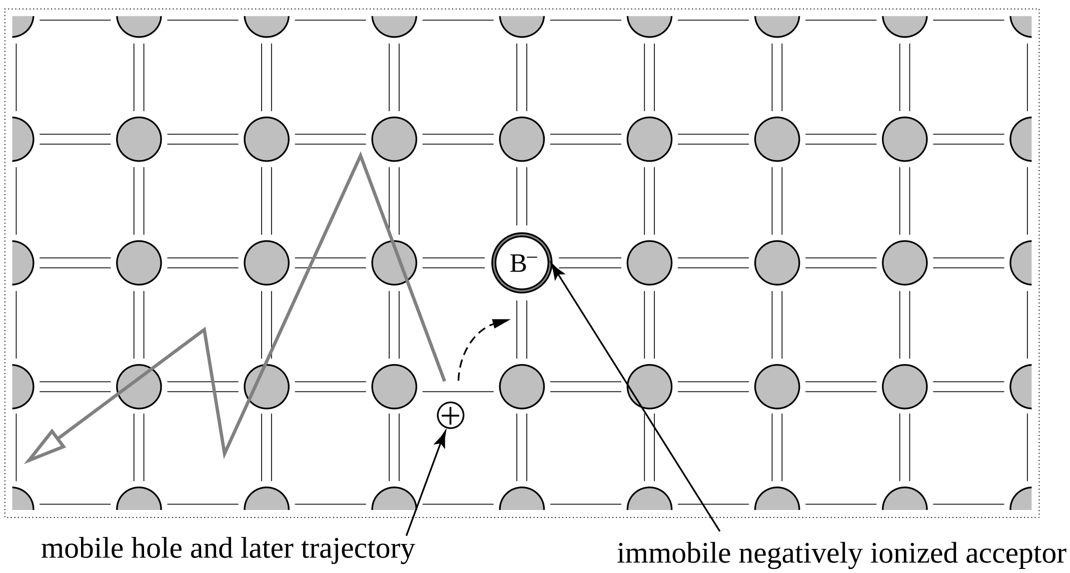
Chemical reaction analogy:
dissolve a bit of KOH into water ⇒ $[OH^-] \uparrow$, $[H^+] \downarrow$

B. Acceptors: introduce holes to the semiconductor (but not electrons)

- For Si, group-III atoms with 3 valence electrons (B)

IIB	IIIA	IVA	VA	VIA
	5 B	6 C	7 N	8 O
	13 Al	14 Si	15 P	16 S
30 Zn	31 Ga	32 Ge	33 As	34 Se
48 Cd	49 In	50 Sn	51 Sb	52 Te

- 3 electrons used up to bond to neighboring Si atoms
- 1 bonding site "unsatisfied": easy to "accept" neighboring bonding electron to complete all bonds ⇒ at room temperature, each acceptor releases 1 hole that is available to conduction
- acceptor site become negatively charged (fixed charge)



Define:

$$N_a \equiv \text{acceptor concentration } [cm^{-3}]$$

- If $N_a \ll n_i$, doping irrelevant

(*intrinsic* semiconductor) $\rightarrow n_o = p_o = n_i$

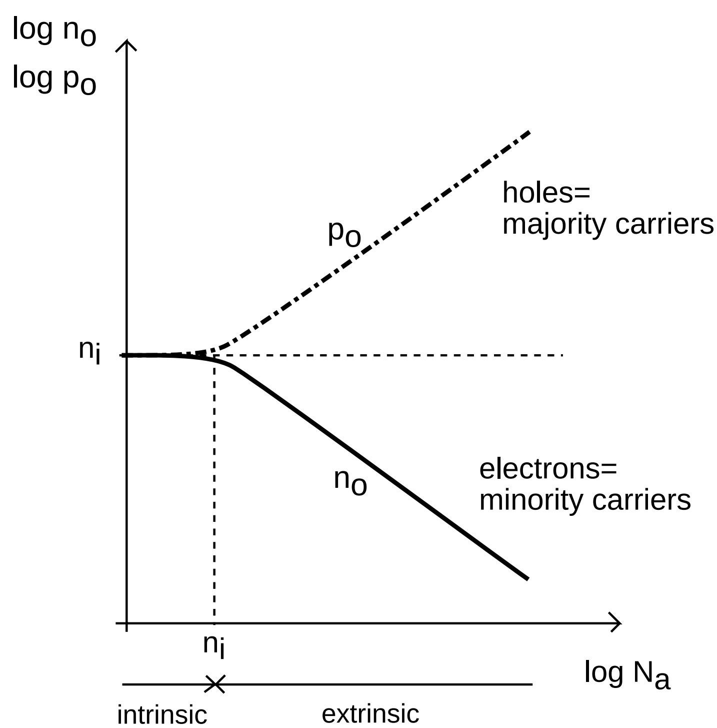
• If $N_a \gg n_i$, doping controls carrier concentrations (*extrinsic* semiconductor) $\rightarrow$

$$p_o = N_a \qquad\qquad n_o = \frac{n_i^2}{N_a}$$

Note: $p_o \gg n_o$: *p-type semiconductor*

Example:
$N_a = 10^{16}\ cm^{-3} \rightarrow p_o = 10^{16}\ cm^{-3}$, $n_o = 10^4\ cm^{-3}$.

In general: $N_a \sim 10^{15} - 10^{20}\ cm^{-3}$



Chemical reaction analogy:
dissolve a bit of H_2SO_4 into water $\Rightarrow$ $[H^+] \uparrow$, $[OH^-] \downarrow$

6. Charge neutrality

Every single atom in a semiconductor (doped or undoped) is charge neutral

$\Rightarrow$ overall charge neutrality must be satisfied

In general:

$$\rho = q(p_o - n_o + N_d - N_a)$$

Check out for $N_d = 10^{17}\ cm^{-3}$, $N_a = 0$:

Solved earlier:

$$n_o = N_d = 10^{17}\ cm^{-3},\ p_o = \frac{n_i^2}{N_d} = 10^3\ cm^{-3}$$

Hence:

$$\rho \neq 0 \quad !!$$

What is wrong??

Nothing is wrong!

We just made an approximation when we said $n_o = N_d$.

We should really solve the following system of equations (for $N_a = 0$):

$$p_o - n_o + N_d = 0$$

$$n_o p_o = n_i^2$$

Solution in textbook (§2.3).

[error in most practical circumstances too small to matter]

Summary

- In a semiconductor, there are two types of "carriers": electrons and holes
- In thermal equilibrium and for a given semiconductor $n_o p_o$ is a constant that only depends on temperature:

$$n_o p_o = n_i^2$$

- For Si at room temperature:

$$n_i \simeq 10^{10}\ cm^{-3}$$

- *Intrinsic semiconductor*: "pure" semiconductor.

$$n_o = p_o = n_i$$

- Carrier concentrations can be engineered by addition of "dopants" (selected foreign atoms):
  - n-type semiconductor:

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

  - p-type semiconductor:

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