Lecture 2
Semiconductor Physics (I)

Outline

- Intrinsic bond model : electrons and holes
- Generation and recombination
- Intrinsic semiconductor
- Doping: Extrinsic semiconductor
- Charge Neutrality

Reading Assignment:
Howe and Sodini; Chapter 2. Sect. 2.1-2.3

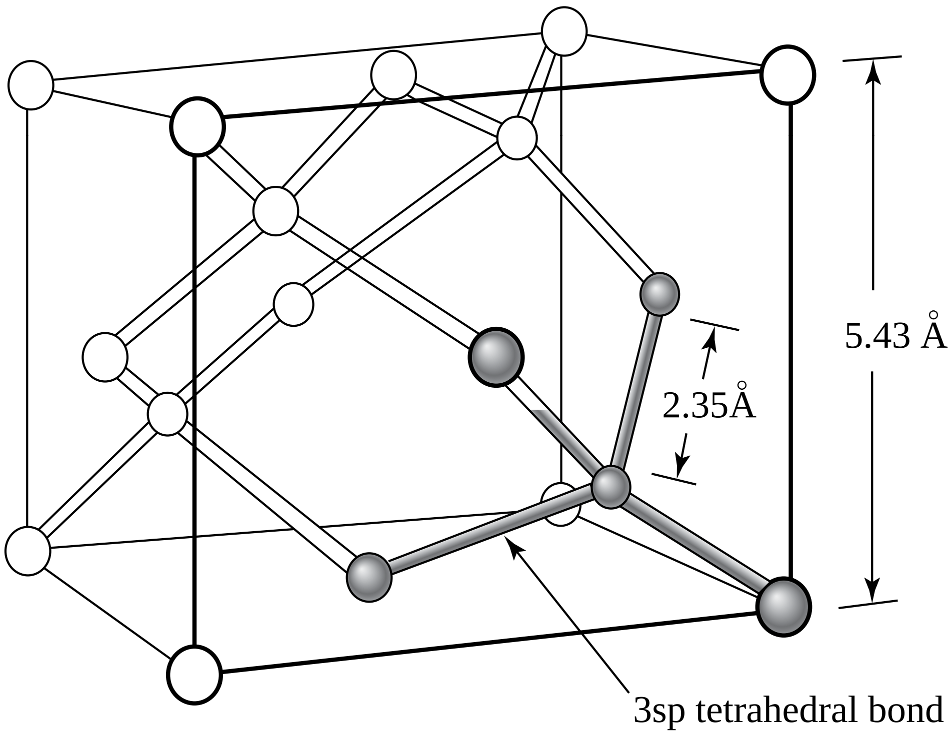
1. Silicon bond model:
electrons and holes

Si is Column IV of the 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

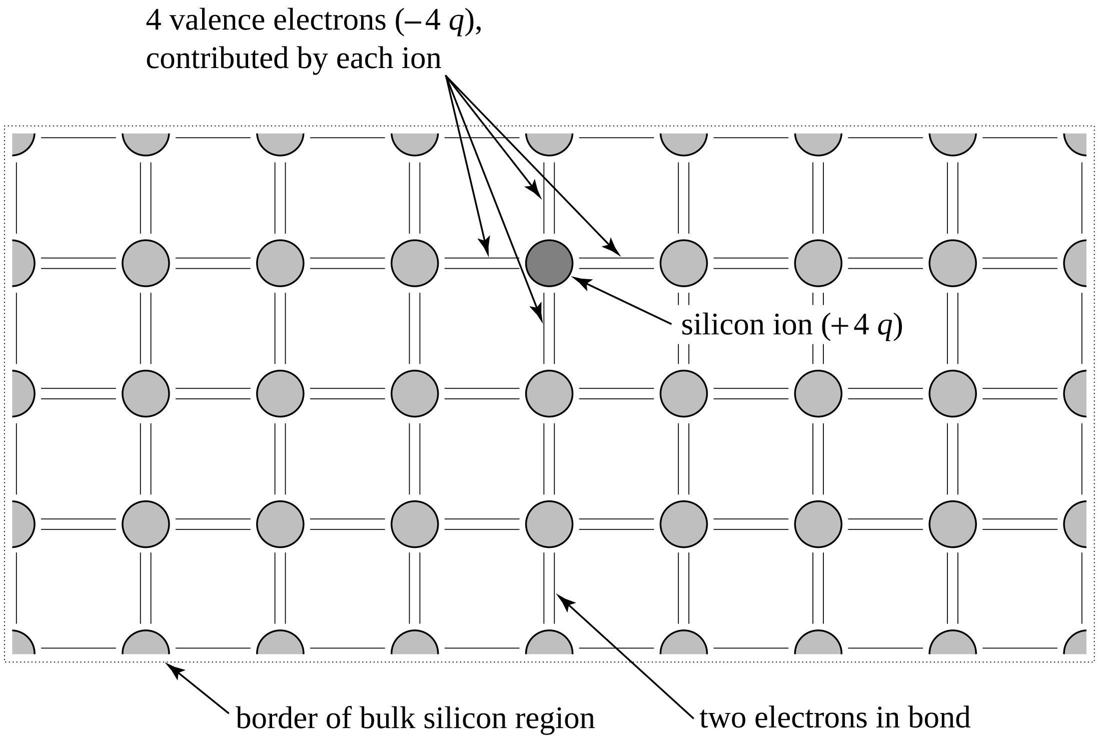
- Electronic structure of silicon atom:
  - 10 core electrons (tightly bound)
  - 4 valence electrons (loosely bound, responsible for most of the chemical properties
- Other semiconductors:
  - Ge, C (diamond form)
  - GaAs, InP, InGaAs, InGaAsP, ZnSe, CdTe (on the average, 4 valence electrons per atom)

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 x 10^{22} cm^{-3}

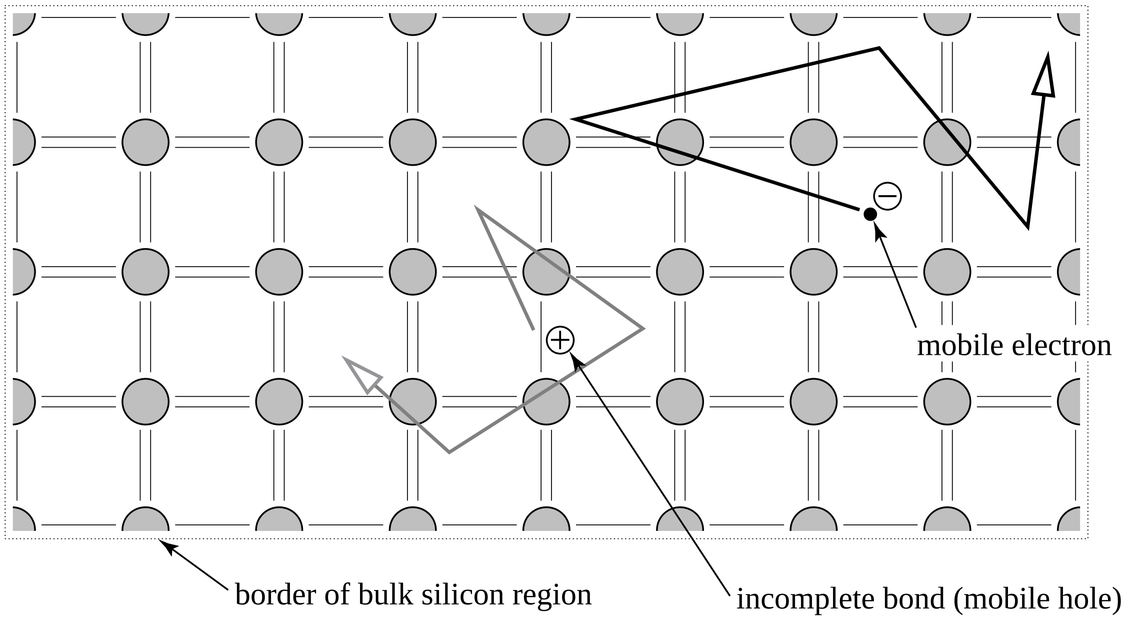
Simple “flattened” model of Si crystal



At 0K:

- All bonds are satisfied
  - $\Rightarrow$ all valence electrons engaged in bonding
- No “free” electrons

At finite temperature



- Finite thermal energy
- Some bonds are broken
- "free" electrons
  - Mobile negative charge, -1.6×10^{-19} C
- "free" holes
  - Mobile positive charge, $+1.6 \times 10^{-19}$ C

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

A few definitions:

- In 6.012, “electron’ means free electron
- Not concerned with bonding electrons or core electrons
- Define:
  - $n \equiv$ (free) electron concentration [cm^{-3}]
  - $p \equiv$ hole concentration [cm^{-3}]

2. Generation and Recombination

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

- Requires energy from thermal or optical sources (or external sources)
- Generation rate: $\mathbf{G = G(th) + G_{opt} + \ldots [cm^{-3} \bullet s^{-1}]}$
- In general, atomic density >> n, p $\Rightarrow$

$$\mathbf{G \neq f(n,p)}$$

  - supply of breakable bonds virtually inexhaustible

RECOMBINATION=formation of covalent bond by bringing together electron and hole

- Releases energy in thermal or optical form
- Recombination rate: $\mathbf{R = [cm^{-3} \bullet s^{-1}]}$
- 1 recombination event requires 1 electron + 1 hole $\Rightarrow$ $\boldsymbol{R \propto n \bullet p}$

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

3. Intrinsic semiconductor

THERMAL EQUILIBRIUM

Steady state + absence of external energy sources

Generation rate in thermal equilibrium: $\mathbf{G_o = f(T)}$

Recombination rate in thermal equilibrium: $\boldsymbol{R_o \propto n_o \bullet p_o}$

In thermal equilibrium:
Every process and its inverse must be EQUAL

$$G_o(T) = R_o \Rightarrow n_o p_o = k_o G_o(T)$$

$$n_i \equiv \textit{\textbf{intr}insic carrier concentration}\ [cm^{-3}]$$

In Si at 300 K ("room temperature"): $n_i \approx 1\text{x}10^{10}\ cm^{-3}$
In a sufficiently pure Si wafer at 300K ("intrinsic semiconductor):

$$\boldsymbol{n_o = p_o = n_i} \approx 1 \times 10^{10}\ \boldsymbol{cm}^{-3}$$

n_i is a very strong function of temperature

$$\mathbf{T} \uparrow \Rightarrow \mathbf{n_i} \uparrow$$

4. Doping

Doping = engineered introduction of foreign atoms to modify semiconductor electrical properties

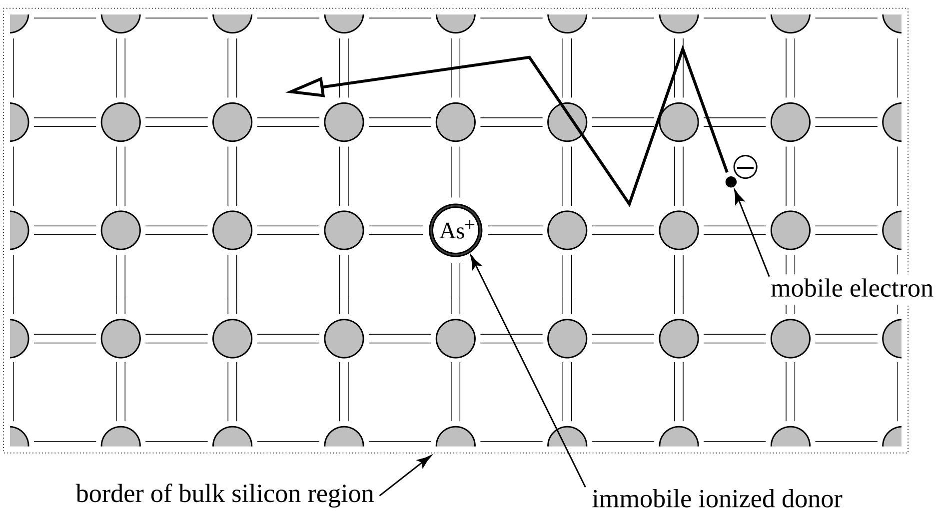
A. DONORS:

- Introduce electrons to semiconductors (but not holes)
- For Si, group V elements 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

Doping: Donors Cont'd...

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



Define:

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

- If $N_d << n_i$, doping is irrelevant
  - Intrinsic semiconductor$\rightarrow n_o = p_o = n_i$

Doping: Donors Cont'd...

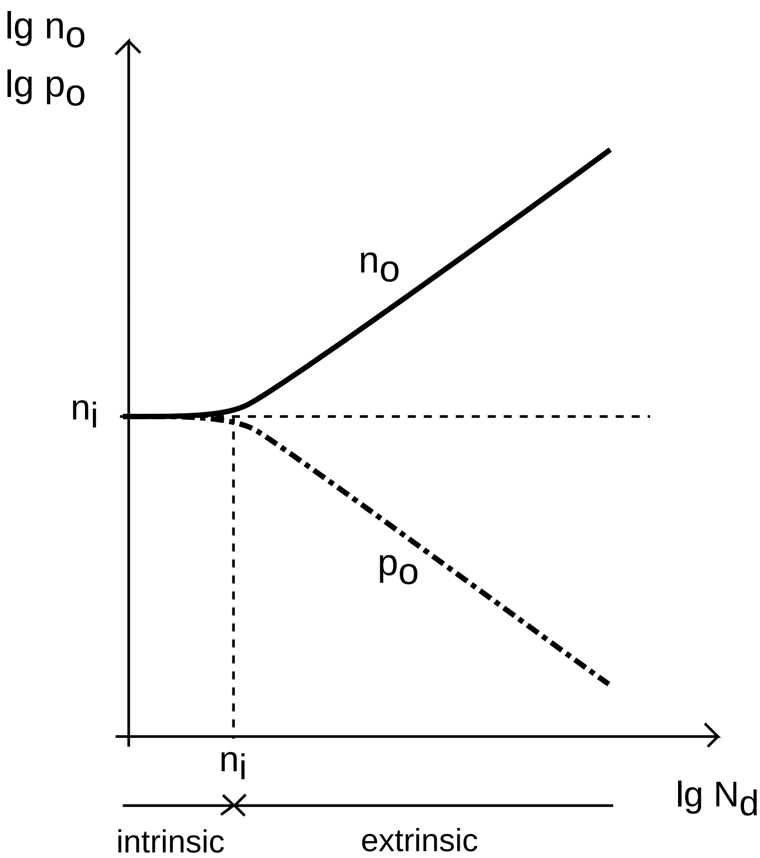
- If $N_d >> n_i$, doping controls carrier concentration
  - Extrinsic semiconductor $\Rightarrow$ $\mathbf{n}_0 = \mathbf{N_d}$ $\qquad \mathbf{p_o} = \frac{\mathbf{n_i^2}}{\mathbf{N_d}}$

Note: $n_o >> p_o$: 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: $N_d \approx 10^{15} - 10^{20}$ cm^{-3}



- **Electrons** = majority carriers
- **Holes** = minority carriers

Doping : Acceptors

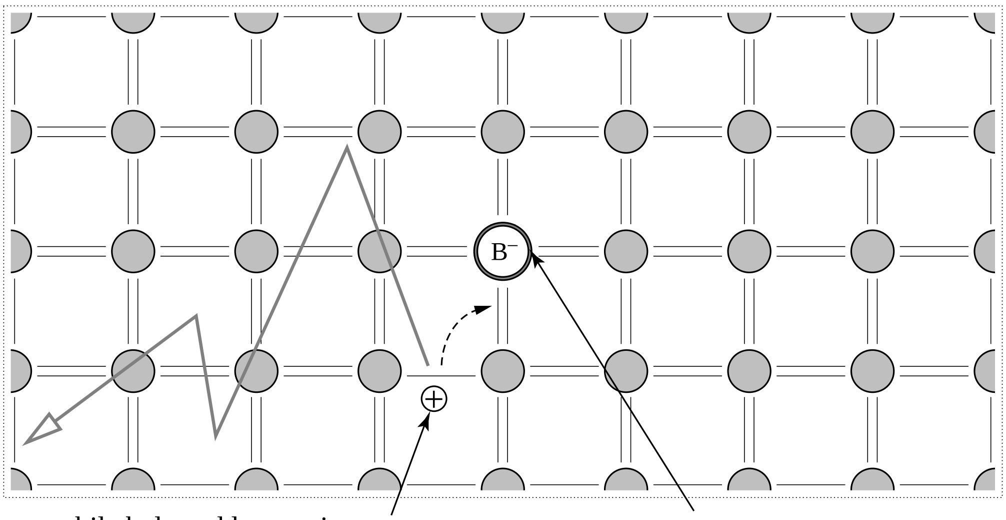
A. ACCEPTORS:

- Introduce holes to semiconductors (but not electrons)
- For Si, group III elements 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

Doping: Acceptors Cont'd...

- 3 electrons participate in bonding
- 1 bonding site "unsatisfied" making it easy to "accept" neighboring bonding electron to complete all bonds $\Rightarrow$
  - at room temperature, each acceptor "releases" 1 hole that is available for conduction
- Acceptor site become negatively charged (fixed charge)



Define:

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

- If $N_a << n_i$, doping is irrelevant
  - Intrinsic semiconductor$\rightarrow n_o = p_o = n_i$

Doping: Acceptors Cont'd...

- If $N_a >> n_i$, doping controls carrier conc.
  - Extrinsic semiconductor $\Rightarrow$

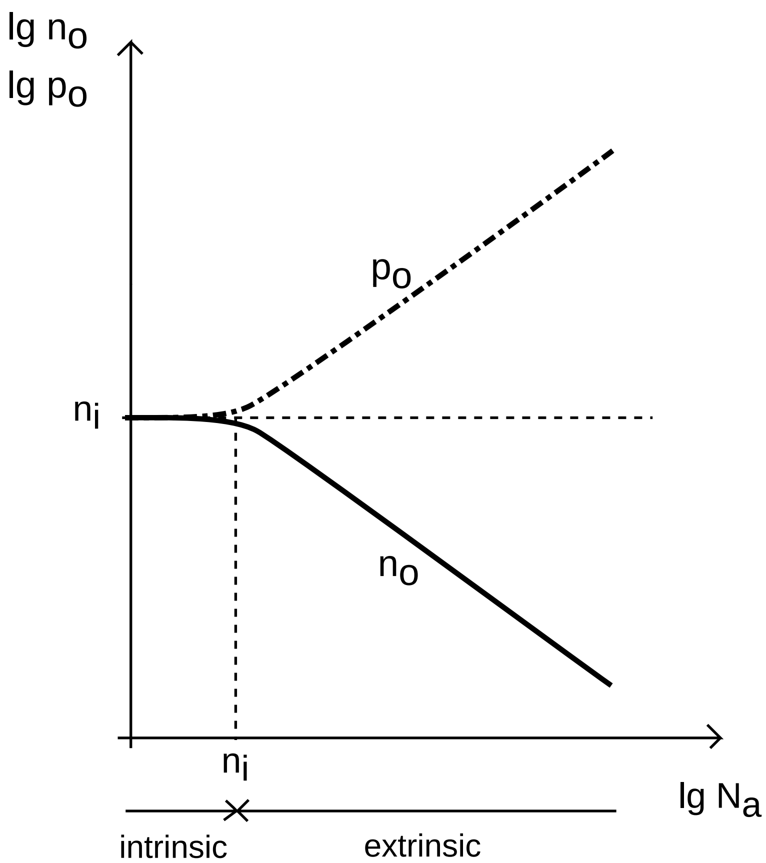
$$p_o = N_a \qquad n_o = \frac{n_i^2}{N_a}$$

Note: $p_o >> n_o$: p-type semiconductor

Example:

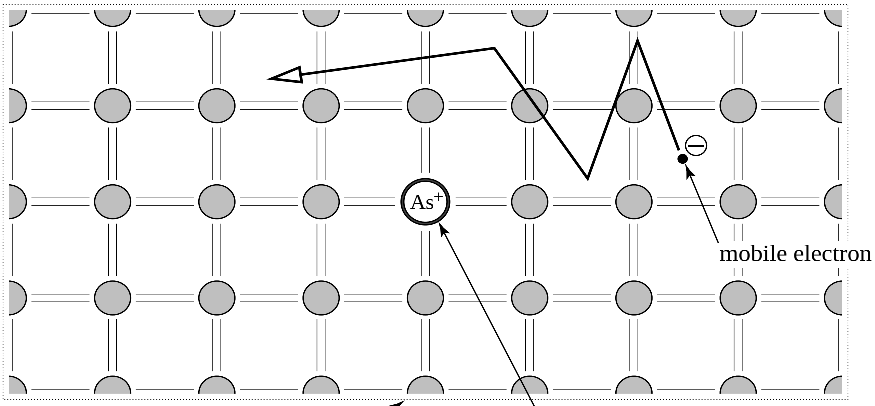
$N_a=10^{17}$ cm^{-3} $\rightarrow$ $p_o=10^{17}$ cm^{-3} , $n_o=10^3$ cm^{-3}

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



- **Holes** = majority carriers
- **Electrons** = minority carriers

5. Charge Neutrality



- The semiconductor remains charge neutral even when it has been doped
  - $\Rightarrow$ Overall charge neutrality must be satisfied
- In general:

$$\rho = \mathbf{q}\left(\mathbf{p_o} - \mathbf{n_o} + \mathbf{N_d} - \mathbf{N_a}\right)$$

Let us examine this for $N_d = 10^{17}$ cm^{-3}, $N_a = 0$

We solved this in an earlier example:

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

Hence: $\rho \neq 0$!!

What is wrong??

Charge Neutrality cont'd...

Nothing wrong!

We just made the approximation when we assumed that $n_o = N_d$

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

$$\boxed{\begin{gathered} p_o - n_o + N_d = 0 \\ n_o p_o = n_i^2 \end{gathered}}$$

Solution and discussion tomorrow in recitation.

Error in most practical circumstances too small to matter!

Summary

Why are IC's made out of Silicon?

SILICON IS A SEMICONDUCTOR—
a very special class of materials

- Two types of "carriers" (mobile charge particles):
  – electrons and holes
- Carrier concentrations can be controlled over many orders of magnitude by addition "dopants"
  – selected foreign atoms
- Important Equations under Thermal Equilibrium conditions
  – Charge Neutrality
  – Law of Mass Action

$$p_o - n_o + N_d - N_a = 0$$

$$n_o p_o = n_i^2$$

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