

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

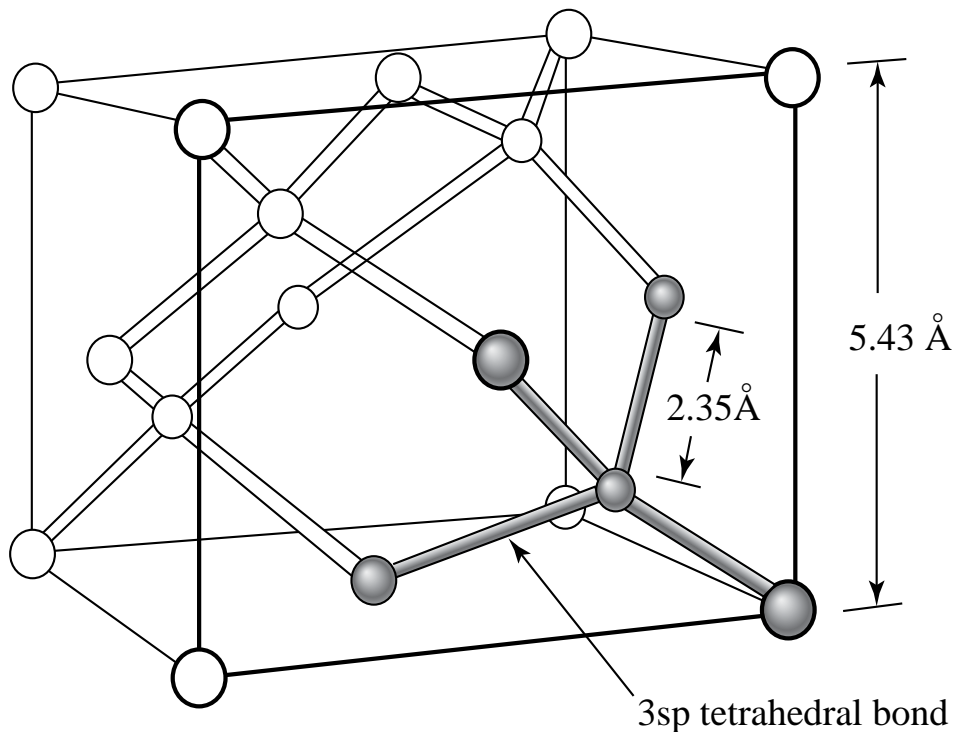
1. Silicon bond model: electrons and holes

Si is in Column IV of the periodic table:

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

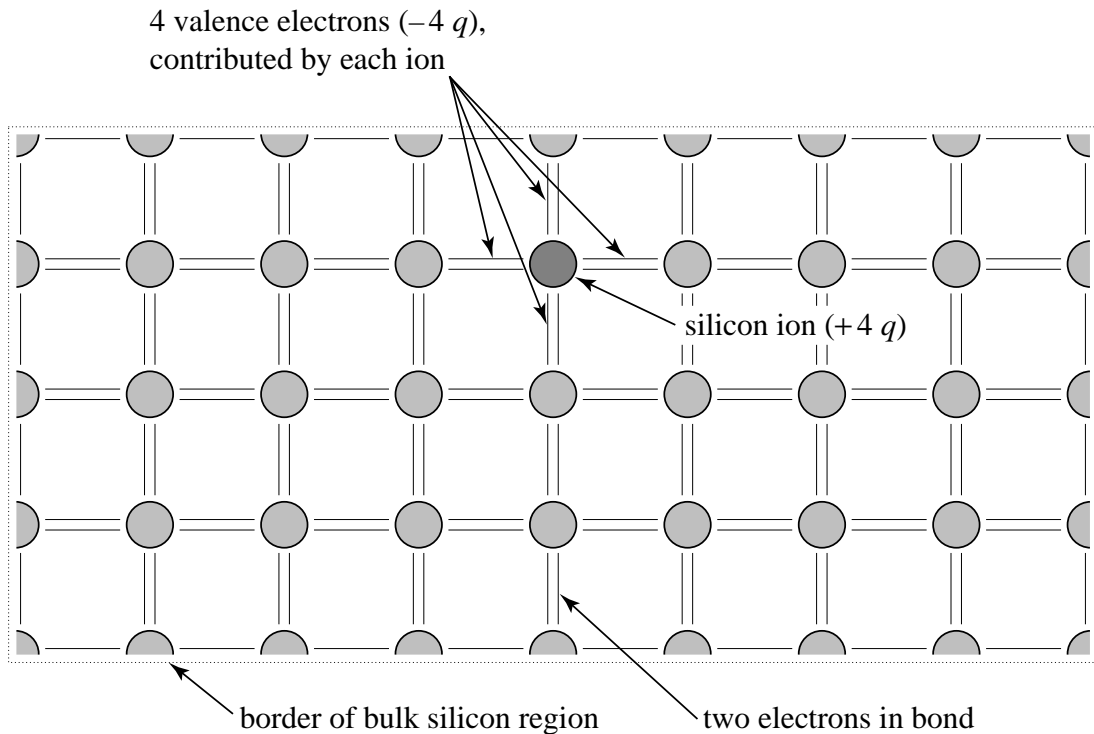
- Electronic structure of silicon atom:
 - 10 core electrons (tightly bound)
 - 4 valence electrons (loosely bound, responsible for most of the chemical properties)
- Other semiconductors:
 - Ge, C (diamond form)
 - GaAs, InP, InGaAs, InGaAsP, ZnSe, CdTe (on the average, 4 valence electrons per atom)

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 : $5 \times 10^{22} \text{ cm}^{-3}$

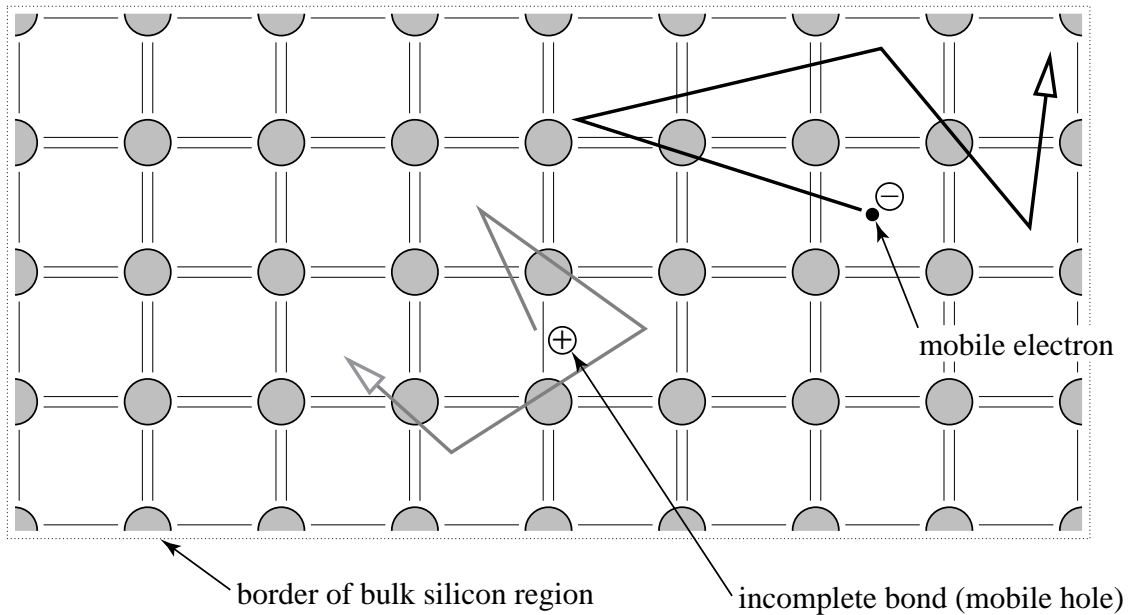
Simple “flattened” model of Si crystal



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, $-1.6 \times 10^{-19} \text{ C}$
- “free” holes
 - Mobile positive charge, $+1.6 \times 10^{-19} \text{ C}$

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: $G = G(\text{th}) + G_{\text{opt}} + \dots [\text{cm}^{-3} \cdot \text{s}^{-1}]$
- In general, atomic density $\gg n, p \Rightarrow$

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

- 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: $R = [\text{cm}^{-3} \cdot \text{s}^{-1}]$
- 1 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. Intrinsic semiconductor

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:

Every process and its inverse must be EQUAL

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

$$n_o p_o = n_i^2(T) \quad \text{Only function of T}$$

$n_i = \textit{intrinsic carrier concentration (cm}^{-3}\text{)}$

In Si at 300 K (“room temperature”): $n_i \approx 1 \times 10^{10} \text{ cm}^{-3}$

In a sufficiently pure Si wafer at 300K (“intrinsic semiconductor”):

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

n_i is a very strong function of temperature

$$T \uparrow \Rightarrow n_i \uparrow$$

4. Doping

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

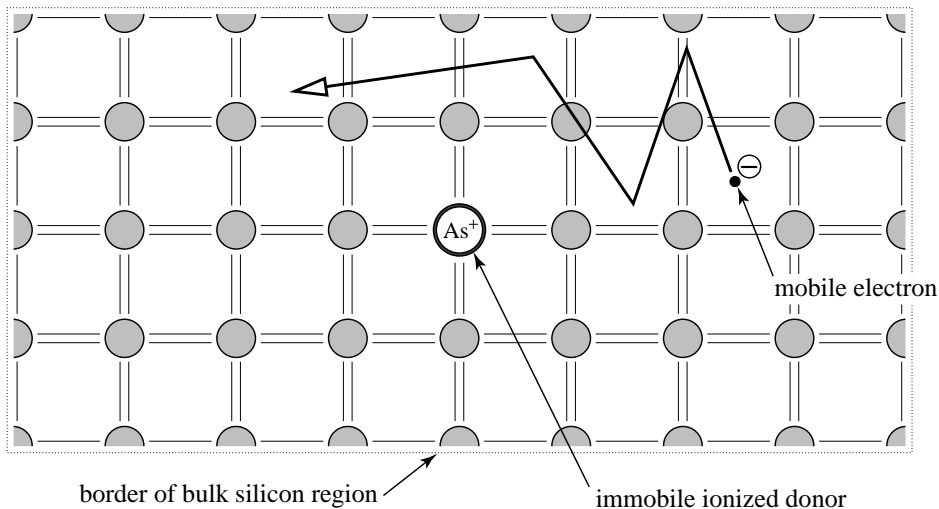
A. DONORS:

- Introduce electrons to semiconductors (but not holes)
- For Si, group V elements with 5 valence electrons (As, P, Sb)

	IIIA	IVA	VA	VIA	
	5 B	6 C	7 N	8 O	
	13 Al	14 Si	15 P	16 S	
IIB	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 $N_d \ll n_i$, doping is irrelevant
 - Intrinsic semiconductor $\rightarrow n_o = p_o = n_i$

Doping: Donors Cont'd...

- If $N_d \gg n_i$, doping controls carrier concentration
 - Extrinsic semiconductor \Rightarrow

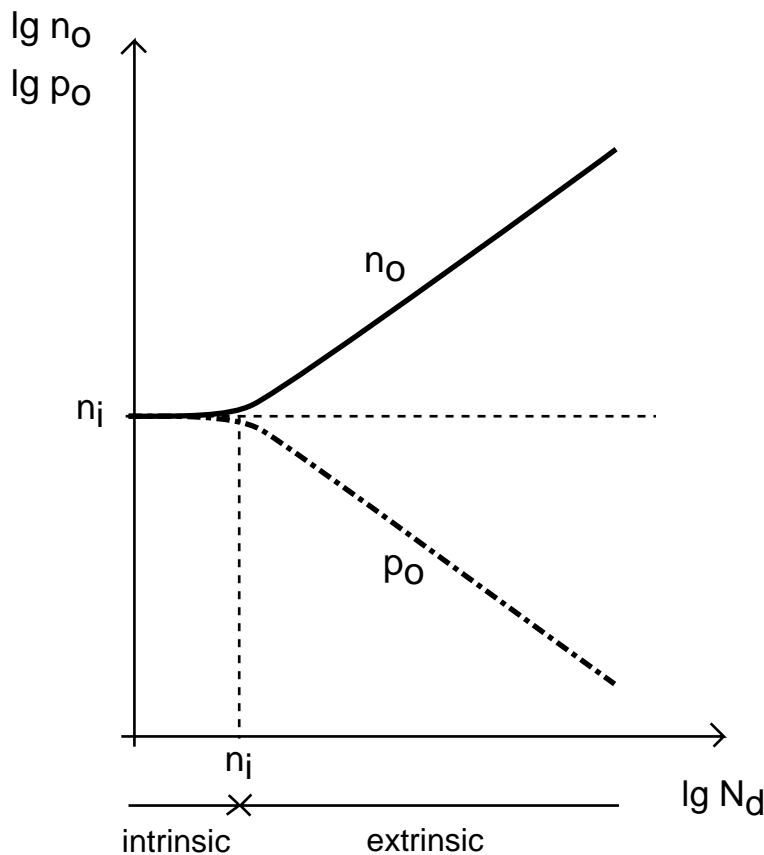
$$n_o = N_d \quad p_o = \frac{n_i^2}{N_d}$$

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

Example:

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

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



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

Doping : Acceptors

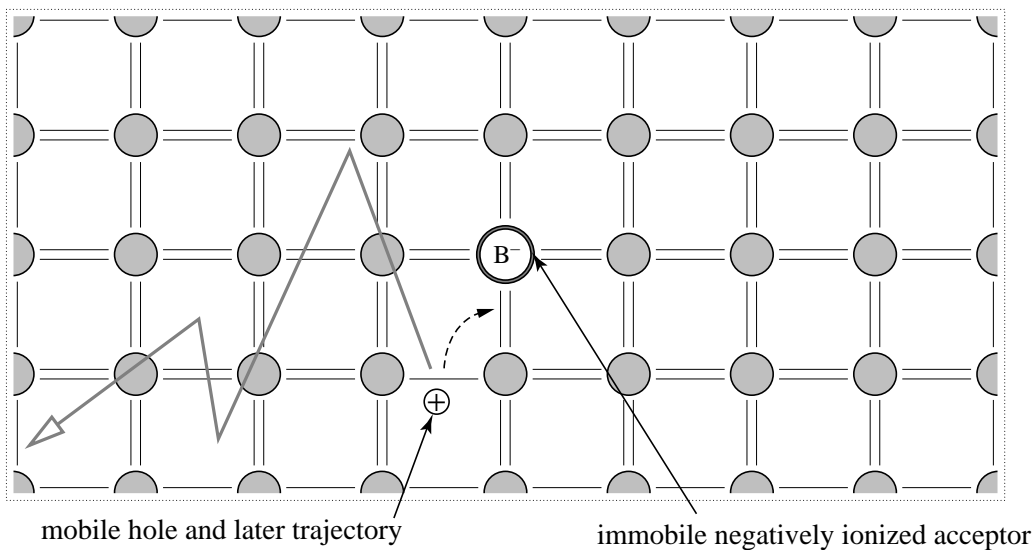
A. ACCEPTORS:

- Introduce holes to semiconductors (but not electrons)
- For Si, group III elements with 3 valence electrons (B)

	IIIA	IVA	VA	VIA	
	5 B	6 C	7 N	8 O	
	13 Al	14 Si	15 P	16 S	
IIB	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:

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

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

Doping: Acceptors Cont'd...

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

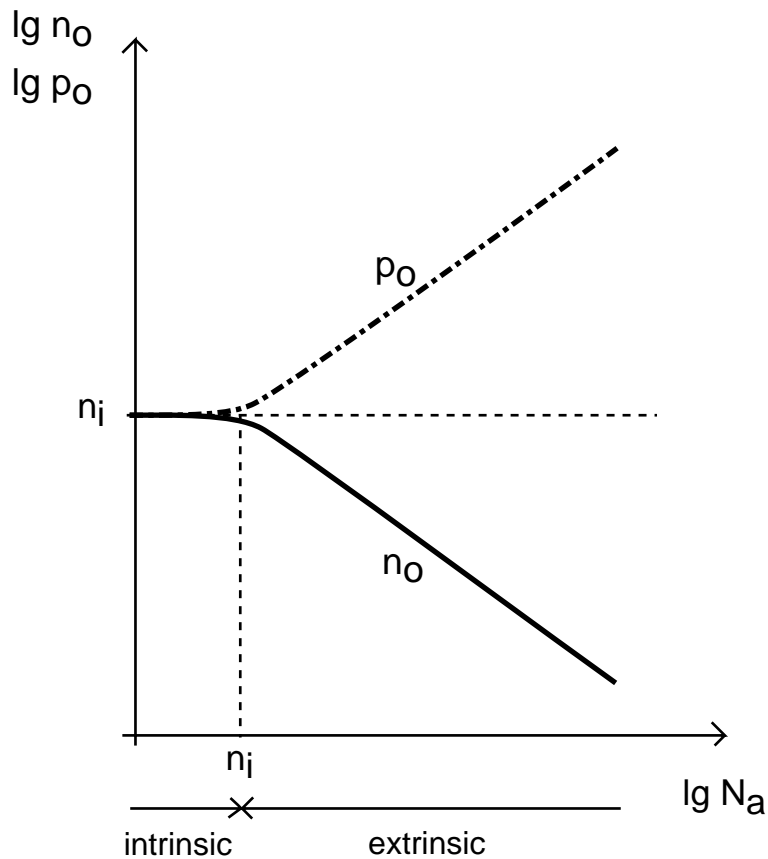
$$p_o = N_a \quad n_o = \frac{n_i^2}{N_a}$$

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

Example:

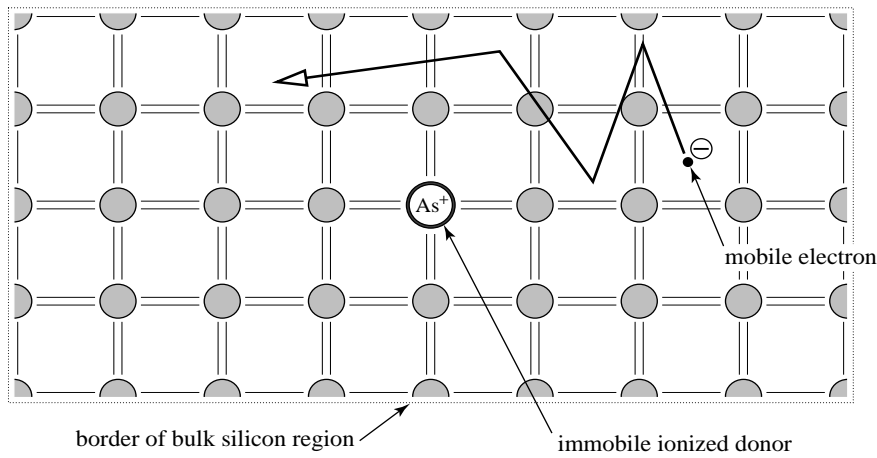
$$N_a = 10^{17} \text{ cm}^{-3} \rightarrow p_o = 10^{17} \text{ cm}^{-3}, n_o = 10^3 \text{ cm}^{-3}$$

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



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

5. Charge Neutrality



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

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

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

We solved this in an earlier example:

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

Hence: $\rho \neq 0 !!$

What is wrong??

Charge Neutrality cont'd...

Nothing wrong!

We just made an approximation when we assumed that

$$n_o = N_d$$

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 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 of “dopants”
 - selected foreign atoms
- Important Equations under Thermal Equilibrium conditions
 - Charge Neutrality
 - Law of Mass Action

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

$$n_o p_o = n_i^2$$